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## CHAPTER 1

### 1.1 INTRODUCTION

Buildings are becoming larger and more complex, and the economic environment in which they operate is becoming more uncertain. Building designers today are encountering several difficult problems in their design task. These include :

- i) an increasing number of alternatives to consider;
- ii) assessment of technological innovations, many of which are unproven in terms of initial cost, reliability and future costs;
- iii) prediction of the future operating and maintenance cost environment for the various subsystems comprising a building;
- iv) difficulty of co-ordinating the design activities of various professional disciplines involved in the design process;
- v) an increase in the complexity of interactions between alternatives;
- vi) more stringent design codes;
- vii) a design fee structure which has not kept pace with the increase in the complexity of the design task;  
and
- viii) increasing designer's liability.

There is a need for a low cost computer-based design decision tool for screening alternatives in the preliminary design phase which accounts for investor criteria and constraints and for interactions between building subsystems. The need for such a tool is particularly pressing with respect to the design of building energy systems. The components of such a tool include :

- a) Preliminary analysis and design routines - In this component, alternative types (e.g. different system types) and values for the variables describing each alternative type must be determined. Also, the interaction between different systems and source of the interactions must be considered.
- b) Economics - Development of this component requires :
  1. formulation of performance measures which reflect investor's interests;
  2. modeling of time variations;
  3. treatment of risk;
  4. identification and inclusion of forecasting techniques; and
  5. development of cost models.
- c) Optimization - For this component, we need to adapt optimization techniques to help in selecting subsystem alternatives and in optimizing the design of the alternative selected. Also, a co-ordination routine must be developed in order to interface the designs of the various building subsystems.



- d) Data base - A data base for capital and future costs must be established. Collection of data and its reliability is one of the major issues in both phases described in a) and b).

In this study, the main focus will be on the economics component of the design tool.

Most research done to date on developing computer aids as described above has focussed on either selecting values for design variables, given the type of system, or studying the interaction between given subsystems.

The energy crisis since 1973 has lent greater urgency to the task of developing such a system. The sudden changes in the price of various sources of energy (see Fig. 1-1), and also the increasing related rate of inflation, make it necessary to use performance measures in decision making which account for future costs. This means we probably have to change our approach to the initial design of the building, both in terms of initial cost (to avoid high future costs), and the alternatives we select.

## 1.2 OBJECTIVES

In order to develop a decision tool along the line previously discussed, the following issues that relate to the economic component must be resolved :

- 1) formulation, in quantitative terms of objective functions for different owner types;

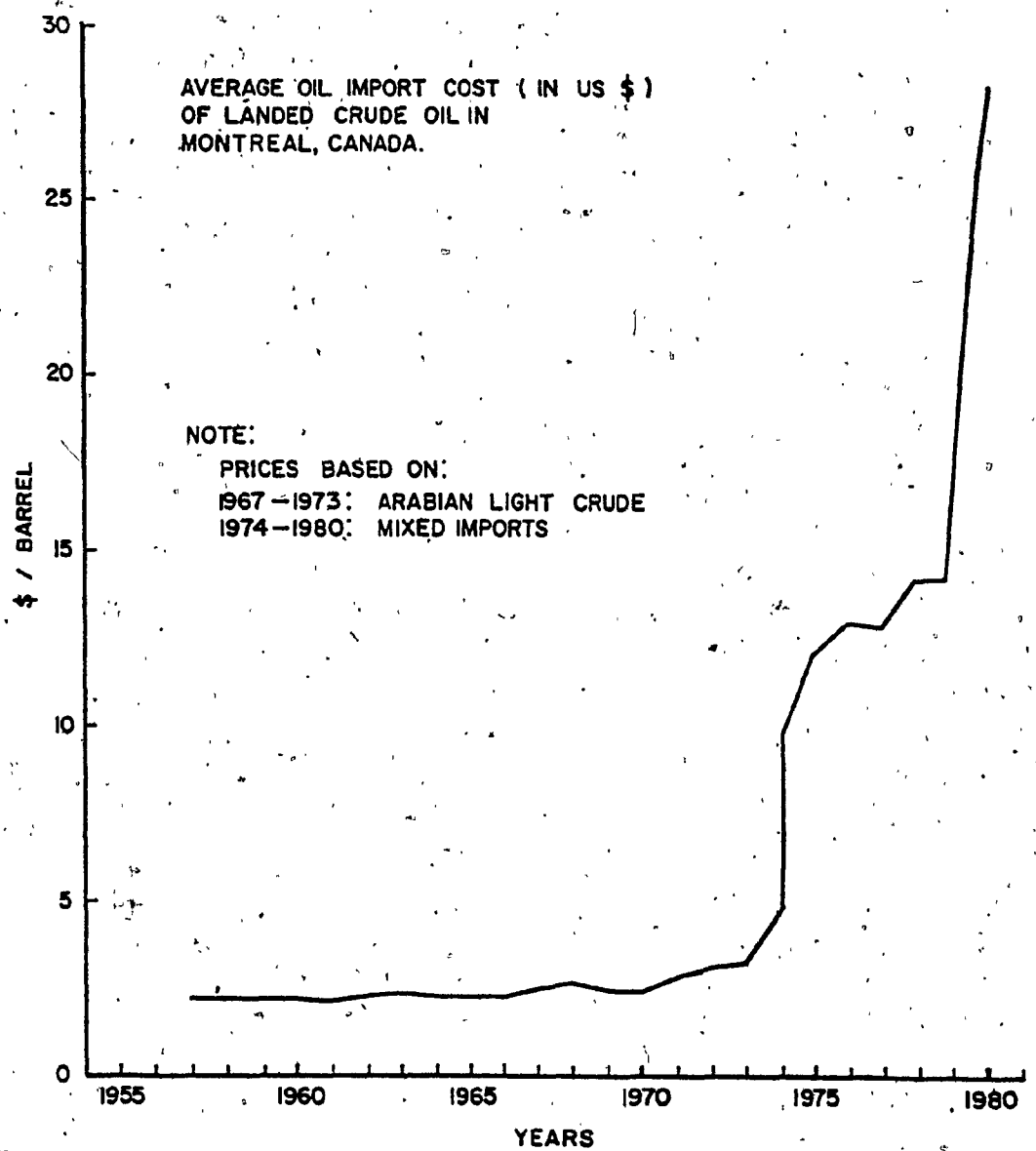


FIG.1.1 WORLD PRICE OF IMPORTED OIL

- ii) treatment of the design problem as a multi-attributed decision making one; and
- iii) measurement, quantification and incorporation of risk into the decision-making process.

1.2.1 The specific goals for this study are :

- i) to formulate the building design problem for different investor viewpoints;
- ii) to develop a detailed statement of an objective function which measures life-cycle cost;
- iii) to formulate different time model types;
- iv) to demonstrate how risk can be measured and quantified for the function identified in ii);
- v) to show how risk can enter into the decision-making process, both for selecting alternatives at the sub-system level, given specified values for co-ordination variables, and how to pick the optimal design of a system comprised of a set of subsystems.
- vi) to develop an interactive computer package to be used for assessing the relative merits of various decisions; and
- vii) to examine an actual case study to determine if one makes different design decisions for different design criteria.

The basic hypotheses of this study are:

- 1) Risk analysis provides additional information for the decision-maker (investor/designer), which helps him to forecast more accurately, and to make better decisions.
- 2) Identification of risk sources and the relative magnitude of the risk from each source assists the designer in allocating design resources to critical life-cycle cost components; and
- 3) Design decision tools helps the designer in examining a larger number of design alternatives and choosing the best one.

### 1.3 INVESTOR VIEWPOINTS

Different investor types can be categorized according to their motives. These basic investor types can be identified as:

- i) Speculative builder - A speculative builder is one who constructs the building only for the purpose of selling upon completion. There is little, or no consideration about future costs and operating problems, except as required by existing building codes. The priority of the builder may be stated as:  
Minimize Capital Cost Subject to: Code Constraints.
- ii) Public investment - This type of investment is non-profit and is concerned with all future costs (operation, repair, alteration), as well as with capital cost. It is

important to note that the above statement does not mean that governments always strive to minimize life-cycle cost, for at least two reasons:

- a) capital funds are limited;
- b) funding mechanisms for capital cost and future operating costs differ, with operating funds being easier to obtain.

Because governments do not pay income tax, future costs assume greater importance for public investments than private ones in making trade-offs between capital and future costs. For this case, one or more of several objective functions can be selected for optimization. They include:

1. Maximize NPV or IRR
2. Minimize LCC
3. Minimize Capital Cost
4. Minimize Energy Consumption
5. Minimize Risk
6. Maximize the presence of the government at a certain location,

in which:

NPV = net present value

IRR = internal rate of return

LCC = life cycle cost

Optimization of functions is subject to constraints such as:

1. Capital cost constraints
2. Code constraints
3. Energy budget
4. Risk exposure constraints.

iii) Private investor - For the private owner, minimization of capital cost tends to form the most important criterion. However, he is also interested in minimizing operating costs and future alteration costs. In addition, tax considerations form an integral part of the decision process. Typically, the investor wants to optimize one or more of the following functions:

1. Maximize NPV or IRR
2. Maximize Uniformity of cash flow
3. Minimize LCC
4. Minimize Capital Cost
5. Minimize Risk

subject to:

1. Equity constraints
2. Code constraints
3. Risk exposure constraints
4. Energy budget constraints

#### 1.4 OPTIMIZATION

It is useful to subdivide the optimization problems into four types (Table 1-1). They are:

- Zone 11) Single objective function and deterministic variables
- Zone 21) Single objective function and probabilistic variables
- Zone 12) Multiple objective function and deterministic variables
- Zone 22) Multiple objective function and probabilistic variables

TABLE 1-1  
TREATMENT OF OPTIMIZATION PROBLEMS

| OBJECTIVE<br>FUNCTION<br>VARIABLE<br>TREATMENT | SINGLE CRITERION<br>1   | MULTIPLE CRITERIA<br>2  |
|--|---|---|
| DETERMINISTIC<br>1                             | <p>Optimize one of</p> <ol style="list-style-type: none"> <li>1) Maximize NPV or IRR</li> <li>2) Minimize LCC</li> <li>3) Minimize Capital Cost</li> <li>4) Minimize Operating Cost</li> </ol> <p>Subject to :</p> <ol style="list-style-type: none"> <li>i) Equity constraints</li> <li>ii) Code constraints</li> <li>iii) Future expenditure constraints</li> </ol>   | <p>Optimize two or more of</p> <ol style="list-style-type: none"> <li>1) Maximize NPV or IRR</li> <li>2) Minimize LCC</li> <li>3) Minimize Capital Cost</li> <li>4) Minimize Operating Cost</li> </ol> <p>Subject to :</p> <ol style="list-style-type: none"> <li>i) Equity constraints</li> <li>ii) Code constraints</li> <li>iii) Future expenditure constraints</li> </ol>   |
| PROBABILISTIC<br>2                             | <p>Optimize one of</p> <ol style="list-style-type: none"> <li>1) Maximize NPV or IRR</li> <li>2) Minimize LCC</li> <li>3) Minimize Capital Cost</li> <li>4) Minimize Operating Cost</li> <li>5) Minimize Risk</li> <li>6) Minimize Expected Utility of LCC</li> </ol> <p>Subject to :</p> <ol style="list-style-type: none"> <li>i) Equity constraints</li> <li>ii) Code constraints</li> <li>iii) Future expenditure constraints</li> <li>iv) Risk exposure constraints</li> </ol> | <p>Optimize two or more of</p> <ol style="list-style-type: none"> <li>1) Maximize NPV or IRR</li> <li>2) Minimize LCC</li> <li>3) Minimize Capital Cost</li> <li>4) Minimize Operating Cost</li> <li>5) Minimize Risk</li> <li>6) Minimize Expected Utility of LCC</li> </ol> <p>Subject to :</p> <ol style="list-style-type: none"> <li>i) Equity constraints</li> <li>ii) Code constraints</li> <li>iii) Future expenditure constraints</li> <li>iv) Risk exposure constraints</li> </ol> |

In the probabilistic case, it is important to determine which variables will be treated as deterministic ones and which will be treated as probabilistic. Figure 1-2 depicts the types of random inputs which occur.

- i) Design phase - In this phase, design parameters, such as loads and material strength can be treated either as deterministic or random variables.
- ii) Economic phase - Given the size of a system, cost parameters, and related inputs can be treated deterministically or probabilistically and the resulting output of this phase, profit, capital cost, life-cycle cost, etc., can be treated as deterministic or random variables.

In this study, attention will be directed at treating the economic performance measures as random variables.

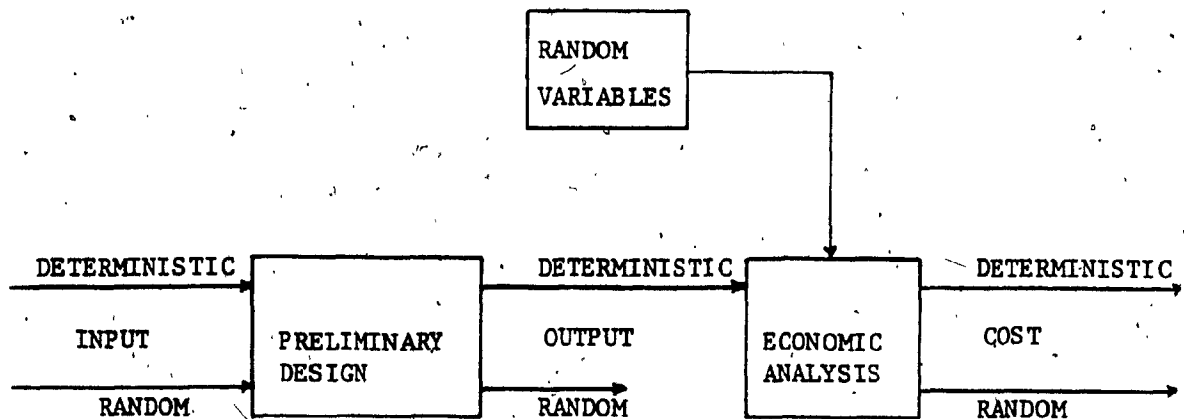


FIG. 1-2 PROBABILISTIC PARAMETERS IN DESIGN



The single objective function optimization problem may be stated, as maximizing or minimizing one specific criterion, subject to implicit or explicit constraints on decision variables as required by building codes, etc., and/or constraints on other economic performance measures.

Max NPV

(1-1)

subject to :

Capital Cost  $\leq C_0$

Risk Level  $\leq R_0$

Energy Cost  $\leq E_0$

where :

$C_0$ ,  $R_0$ ,  $E_0$  are the maximum allowable.

The multiple objective function case could be stated as optimizing a series of objective functions subject to constraints. For example :

Maximize IRR

Minimize LCC

Minimize Capital cost

Minimize Risk

subject to constraints as stated in Eq. (1-1). In this thesis, attention will be focussed on problems described in zones 11 and 21.

### 1.5 LITERATURE REVIEW

Using the framework of Table (1-1), existing literature can be examined :

#### i) Zones (11, 21)

Choudhary [1] and Russell and Choudhary [17] developed a practical computerized design aid for the optimum design of the foundation, structure and enclosure systems of light industrial buildings in such a way as to permit trade-offs to be made between these systems, in order to get an optimum overall system performance as measured by capital cost.

Box's [2] optimization method was employed in this study and was demonstrated to be useful for co-ordinating the design of the building subsystems considered.

#### ii) Zone 21

a) Russell [3] analyzed the building energy system. He introduced the life-cycle cost formulation, which includes both the design aspect and economic factors. He noted that economic and environmental variables regarding political, social, environmental and inflation problems which impact on capital costs and operating costs during the life of the building are largely uncontrollable, and the risk level arising from them can be very high. The design

variables describing the physical characteristics and interaction between large building subsystems are, however, controllable, and can be selected so as to reduce the clients risk exposure. The formulation of life-cycle cost given in reference [3] forms a basis for this study.

b) Wilson and Templeman [4] in their study went one step further and gave almost a complete picture of an optimum thermal design of an office building. They assumed that the structure of the building, including internal and external configuration, ceiling, walls, floor, partition size and material are known. Also, some high level decisions, such as the type of heating system, energy source (e.g. fuel oil) are already made. The purpose of this paper was to get the balance point in the tradeoff between thermal subsystem and other subsystems. The objective function selected was to minimize life-cycle cost (tradeoff between insulation thickness, fuel consumption, system size and its efficiency). Geometric programming was used for optimization of the design. As a conclusion, the authors stated that, for optimum thermal design in buildings, a higher degree of

insulation than is presently used is needed.

In this thesis work, the above-stated conclusion will be looked at in a case study (Chapter 5).

#### 1.6 THESIS OVERVIEW

Development of life-cycle costing relationships is treated in Chapter 2. Chapter 3 deals with risk analysis and methods to quantify risk. Also, different methods for ranking alternatives are presented in this chapter. The computer program for computing life cycle cost, including consideration of risk, is described in Chapter 4. An actual case study will be presented in Chapter 5. Conclusions and recommendations for future studies are presented in Chapter 6. A listing and typical output of the computer program which is described in Chapter 4 are presented in Appendix A.

## CHAPTER 2

### 2.1 OBJECTIVES

The objectives of this chapter are :

- i) To summarize the use of continuous compounding for cost modeling;
- ii) to demonstrate how a fundamental relationship for life cycle cost can be obtained from the net present value (NPV) equation which measures total project performance;
- iii) to assess the information required for a life cycle cost analysis; and
- iv) to identify how controllable design decisions and uncontrollable time effects are reflected in the life cycle cost relationship.

### 2.2 MODELING WITH CONTINUOUS FUNCTIONS

In most, if not all, major building projects, revenue and expense items flow throughout the year, often in a non-uniform manner. Consequently, in theory, greater accuracy can be obtained by using continuous modeling as opposed to discrete modeling of cash flows. As well, certain modeling advantages occur when continuous compounding is used, e.g. in conducting risk analysis and in performing sensitivity analysis. Hence, before examining the issue of life cycle costing, the use of continuous compounding is described.

Consider the case where we have the present sum of  $P$  at time zero with  $r$  being the nominal interest rate, which is computed and compounded  $m$  times in a year (Fig. 2-1)

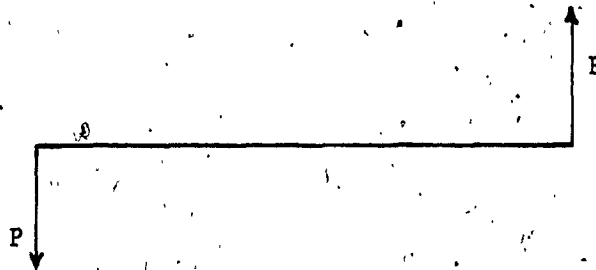


FIG. (2-1) DISCRETE CASH FLOW DIAGRAM

Thus, for each period, the effective interest rate is  $r/m$ .

Then the future worth of sum  $P$  is:

$$F = P (1 + r/m)^m \quad (2-1)$$

and the effective annual interest rate  $\gamma$ , which is defined to be the exact annual rate which takes into account the compounding which occurs within a year [5] is:

$$\gamma = \frac{P (1 + r/m)^m - P}{P} = (1 + r/m)^m - 1 \quad (2-2)$$

When  $m \rightarrow \infty$  (continuous compounding), the effective interest rate becomes:

$$Y = \lim (1 + \frac{r}{m})^m - 1 = e^r - 1 \quad (2-3)$$

and the future worth sum  $F$  is:

$$F = P e^{rt} \quad \text{or} \quad P = F e^{-rt} \quad (2-4)$$

which is the fundamental relationship for continuous compounding.

In the general case of continuous cash flows, as opposed to discrete flows (Fig. 2-2), during time interval  $\Delta t$ ,  $CF(t)$ .  $\Delta t$  dollars flow, where  $CF(t)$  is the cash flow at time  $t$ .

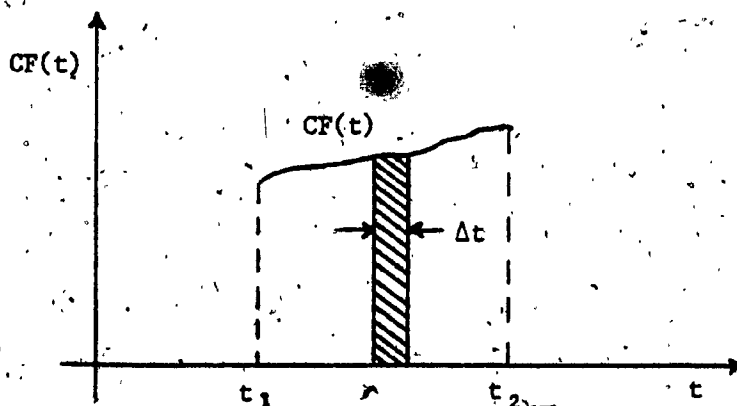


FIG. (2-2) CONTINUOUS CASH FLOW DIAGRAM

Thus, using continuous compounding, the present sum of the above cash flow is:

$$P = CF(t) \cdot e^{-rt} \cdot \Delta t \quad (2-5)$$

Summing over all the intervals  $\Delta t$ , and letting  $\Delta t \rightarrow 0$ , we have:

$$P = \int_{t_1}^{t_2} CF(t) \cdot e^{-rt} \cdot dt \quad (2-6)$$

Example 1

To demonstrate the use of the above relationship, consider the case of uniform cash flow (Fig. 2-3a)

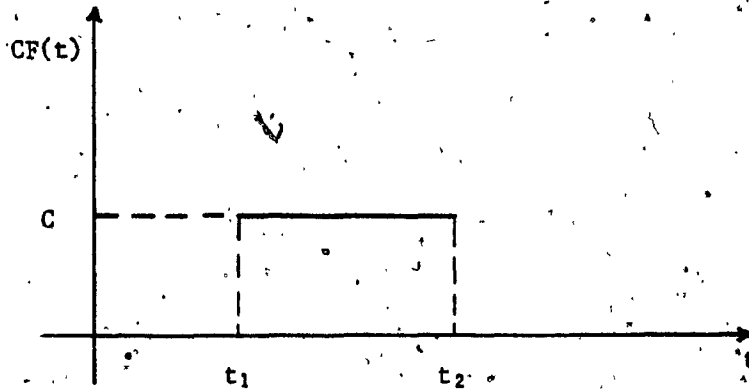


FIG. (2-3a) UNIFORM CONTINUOUS CASH FLOW DIAGRAM



The present sum  $P$  of cash flows from  $t_1$  to  $t_2$  equals:

$$P = \int_{t_1}^{t_2} C \cdot e^{-rt} dt = \frac{C}{r} (e^{-rt_1} - e^{-rt_2}) \quad (2-7)$$

Example 2

In the case of an exponential continuous cash flow with the inflation rate ( $\theta$ ) being constant (i.e.  $CF(t) = C_0 e^{\theta t}$ ), Fig. 2-3(b)

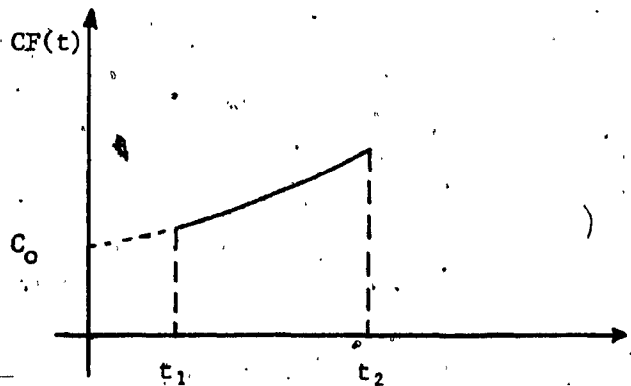


FIG. (2-3b) EXPONENTIAL CONTINUOUS CASH FLOW DIAGRAM

the present sum  $P$  is given by:

$$P = \int_{t_1}^{t_2} C_0 e^{\theta t} e^{-rt} dt = C_0 \int_{t_1}^{t_2} e^{(\theta-r)t} dt \quad (2-8)$$

$$= \frac{C_0}{\theta-r} (e^{(\theta-r)t_2} - e^{(\theta-r)t_1})$$

When  $\theta = r$ ,  $P = C_0 (t_2 - t_1)$

Example 3

Consider the most general case of inflation models, in which  $\theta$  varies with time (Fig. 2-3c).

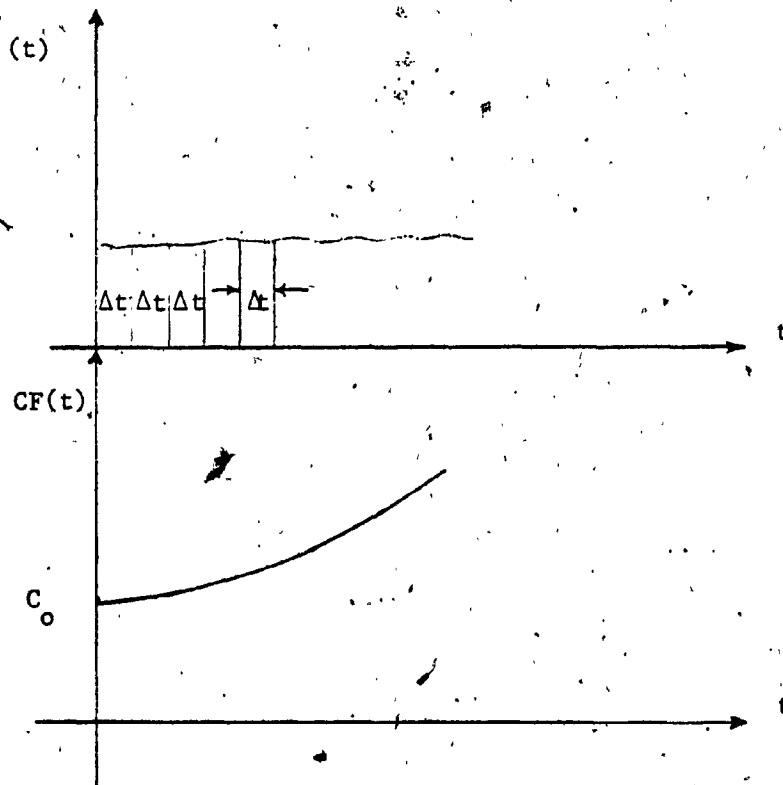


FIG. (2-3c).

FIG. (2-3c) CONTINUOUS CASH FLOW DIAGRAM USING  $\theta = f(t)$

At any time  $t$ , the cash flow can be calculated as :

$$\begin{aligned}
 CF(t) &= C_0 \cdot e^{\theta(t_1)\Delta t} \cdot e^{\theta(t_2)\Delta t} \dots e^{\theta(t_n)\Delta t} \\
 &= C_0 \cdot e^{\theta(t_1)\Delta t + \theta(t_2)\Delta t + \dots + \theta(t_n)\Delta t} \\
 &= C_0 \cdot e^{\sum_{i=1}^n \theta(t_i)\Delta t} \\
 &= C_0 \cdot e^{\int_0^t \theta(t) dt}
 \end{aligned}$$

Let  $\Delta t \rightarrow 0$ ; then the above equation becomes :

$$CF(t) = C_0 e^{\int_0^t \theta(\tau) \cdot d\tau} \quad (2-9)$$

and the present worth of the cash flow  $C(t)$  is :

$$P = \int_0^T C_0 \cdot e^{\int_0^t \theta(\tau) \cdot d\tau} \cdot e^{-rt} \cdot dt \quad (2-10)$$

### 2.3 NET PRESENT VALUE

A fundamental criterion for evaluating an investment and comparing investment alternatives is the net present value criterion. Its use in real estate investment projects is well documented [5, 6].

The net present value relationship gives the present value of all future after-tax cash flows (including ultimate disposal of the property (Fig. (2-4)), i.e. :

$$NPV = \text{present worth of revenues} - \text{present worth of disbursements} \quad (2-11)$$

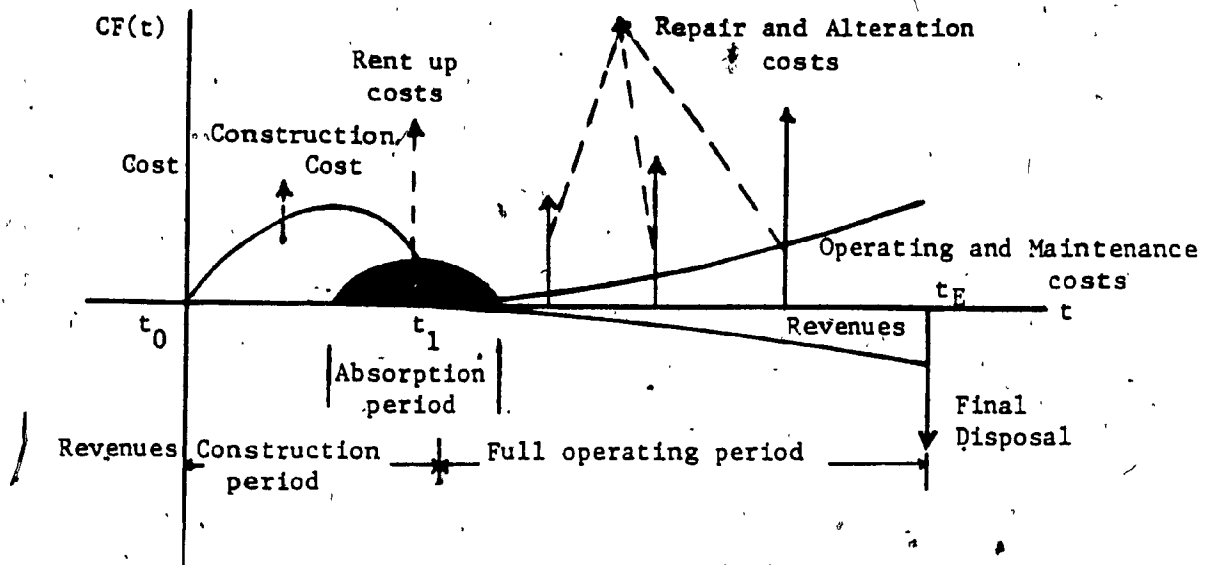


FIG (2-4) CASH FLOW DIAGRAM FOR A BUILDING PROJECT

Figure (2-4) shows four different phases of building project's life cycle and corresponding cash flows.

- i) construction period;
- ii) the absorption period which can overlap the construction period and during which rent up and commissioning costs are incurred;
- iii) operating period which includes revenues, operating and maintenance costs and cyclic repair and alteration costs; and finally
- iv) final disposal of the physical asset.

For any investment, if the net present value is positive, it should be accepted. In the case of negative net present value, other investment alternatives should be tried.

In the most general case, where cash flow (revenues) and cash outflow (disbursements) are considered as continuous functions, using continuous compounding, the above statement can be written as :

$$NPV = \int_0^{t_E} R(t) \cdot e^{-r(t) \cdot t} dt - \int_0^{t_E} C(t) \cdot e^{-r(t) \cdot t} dt \quad (2-12)$$

where :

$R(t)$  = revenues (function of design, time)

$C(t)$  = disbursements including interest payments (function of design, time)

$t$  = time as measured from the starting point ( $t_0 = 0$ )

$r$  = minimum attractive rate of return, which can vary with time in the most general case (for our study,  $r$  represents the after-tax rate of return and includes an allowance for inflation).

The rate of return represents the rate of interest earned on the unrecovered balance of an investment [6]. Whenever income taxes are levied, such taxes tend to reduce the rate of return. The effect of taxes on the cash flow can be expressed as follows [3] :

$$BCTF(t) = R(t) - C(t) - A(t) \quad (2-13)$$

$$ATCF(t) = (1-T) \cdot BCTF(t) + T \cdot [CCA(t) - A(t)] \quad (2-14)$$

where :

$BCTF(t)$  = before-tax cash flow

$ATCF(t)$  = after-tax cash flow

$T$  = tax rate

CCA (t) = capital cost allowance at time t

A (t) = mortgage amortization at time t

Therefore, the income tax consequences for a proposed investment must be estimated, and stipulated minimum attractive rate of return should be an after-tax rate rather than a before-tax rate. Also, this rate must be an inflation-adjusted rate, which in the simplest case is the addition of some desired real rate of return and an estimated inflation rate,  $\theta$ . i.e.

$$r = i + \theta$$

(2-15)

where :

i = real rate of return

$\theta$  = inflation rate

In equation (2-15), the real rate of return can be assumed constant for a specific investment (5). The inflation rate " $\theta$ " is a function of time and consequently the rate of return is a function of time.

Both revenues and disbursements should be measured in terms of current dollars for the following reasons :

1. Taxation - For taxation purposes, we need to deflate the capital cost allowance if we use constant dollars, because it is not indexed (e.g. to prepare budget);
2. To make proper decisions, we need to know the real magnitude of cash flows. Therefore, there is a need to work in terms of current dollars.

3. The inflation rate is not constant, it varies with time. Also, inflation rates for all system elements are not identical (e.g. energy cost and enclosure maintenance cost do not escalate at the same rate).

Now, using the following assumptions:

- a) Inflation is a function of time, which is the most general case ( $\theta = \theta(t)$ );
- b) Cash flow for a cost item can be represented by an inflation model (e.g.  $CF(t) = C_0 e^{\int_0^t \theta(\tau) d\tau}$ );
- c)  $r = i + \theta_G(t)$ , where  $\theta_G(t)$  is an overall inflation rate, existing in the market, which can be called an overall inflation measure (e.g. rate at which consumer price index varies);
- d)  $\theta_i(t) = \theta_G(t) + \theta_{d_i}(t)$ , where  $\theta_i(t)$  is the inflation function for the  $i^{\text{th}}$  cost item, and  $\theta_{d_i}(t)$  is the differential inflation function for the same item;

Equation (2-12) becomes:

$$NPV = \int [R_0 e^{\int_0^t (\theta_G(\tau) + \theta_{dR}(\tau)) d\tau} - C_0 e^{\int_0^t (\theta_G(\tau) + \theta_{dC}(\tau)) d\tau}] e^{-\int_0^t \theta_G(\tau) d\tau} e^{-it} dt$$

where:

- $\theta_{dR}(\tau)$  - differential inflation function of revenues
- $\theta_{dC}(\tau)$  - differential inflation function of disbursements
- $R_0$  - revenues (base year estimate)
- $C_0$  - disbursements (base year estimate)

If the general inflation rate over a long period of time is taken as a constant (i.e.  $\theta_G(t) = \theta_G$ ), then Eq. (2-16) becomes:

$$NPV = \int_0^t [R_0 e^{\int_0^\tau \theta_G d\tau} - C_0 e^{\int_0^\tau \theta_G d\tau}] e^{-it} dt \quad (2-17)$$

or alternatively:

$$NPV = \int_0^t [R_0 e^{\int_0^\tau \theta_R d\tau} - C_0 e^{\int_0^\tau \theta_C d\tau}] e^{-rt} dt \quad (2-18)$$

where:

$\theta_R(\tau)$  = overall inflation function of revenues

$\theta_C(\tau)$  = overall inflation function of disbursements

In Eq. (2-18), we need to predict the overall inflation model. The disbursement component could be divided into two parts - initial cost (construction phase), and future costs (operating phase) (Fig. 2-4). Then, Eq. (2-18) becomes:

$$NPV = \int_0^t [R_0 e^{\int_0^\tau \theta_R d\tau} - (C_{1e} e^{\int_0^\tau \theta_{C1} d\tau} + C_{fe} e^{\int_0^\tau \theta_{Cf} d\tau})] e^{-rt} dt \quad (2-19)$$

where:

$C_1$  = initial cost (function of design and time)



$C_f$  = future cost (function of design and time)

$R_o$  = revenues (function of design and time)

$\theta_{C_i}(\tau)$  = inflation model for initial cost

$\theta_{C_f}(\tau)$  = inflation model for future cost

And more explicitly, using Fig. (2-4) :

$$NPV = \int_{t_1}^{t_E} R_o e^{-rt} dt - \int_{t_0}^{t_1} C_i e^{-rt} dt - \int_{t_1}^{t_E} C_f e^{-rt} dt \quad (2-20)$$

in which :

$$\int_{t_1}^{t_E} C_f e^{-rt} dt$$

$t_0$  is the starting time for construction;

$t_1$  is the finishing time for construction; and

$t_E$  is the end of the study period.

#### 2.4 LIFE CYCLE COSTING (LCC)

The net present value relationship, Eq. (2-20) is not in a form where we can directly identify our architectural and engineering contribution to overall economic performance, both in terms of capital cost and future operating costs.

Normally, one key objective of the owner/developer is to maximize the net present value. Now as architects and engineers, we do not normally know the values of all the inputs that go into determining the net present value. However, we can contribute to maximization of NPV by minimizing total capital cost and the future costs associated with the physical systems of a building [3]. By using this approach, interaction between different design alternatives and revenues are neglected. Also, the effect of different design techniques on duration of project is ignored, unless in formulation of life-cycle

cost, specific allowance is made. In this study, such an allowance is not made.

Thus, the life cycle cost could be defined as :

$$LCC = \text{Présent worth of capital cost} + \text{present worth of future costs} \quad (2-21)$$

The revenues and final disposal of assets are excluded from this relationship (they are assumed to be included in Eq. (2-20)). From Eq. (2-20), LCC can be written as :

$$LCC = \int_{t_0}^{t_1} C_i e^{-rt} dt + \int_{t_1}^{t_E} C_f e^{-rt} dt \quad (2-22)$$

where the future cost itself is composed of different components, i.e. operating, maintenance, repair and alteration (see Fig. 2-4).

For design purposes, it is useful to further decompose the life-cycle cost equation, using a work breakdown structure, such as the Unifomat structure (Table 2-1), which breaks down the building system into two levels, level I which deals with the major building subsystems (e.g. enclosure, structure, mechanical system), and level II which includes the elements of a specific subsystem (e.g. for a mechanical system, the elements are boilers, chillers, etc.).

Then, a general expression for LCC may be written as :

$$LCC = \sum_{j=1}^n (C_{1j} + (1-T) (C_{0j} + C_{mj} + C_{rj} + C_{pj})^* - T.CCA_j) \quad (2-23)$$

\*Note : Alteration and repair costs are assumed to be expensed. In some cases, especially when they are sizeable, they would be capitalized; thus altering the capital cost allowance base.

where :

- $C_{1j}$  = present worth of capital cost of system  $j$
- $C_{0j}$  = present worth of operating cost of system  $j$
- $C_{mj}$  = present worth of maintenance cost of system  $j$
- $C_{rj}$  = present worth of repair cost of system  $j$
- $C_{pj}$  = present worth of alteration cost of system  $j$
- $T$  = tax rate
- $CCA_j$  = capital cost allowance of system  $j$

In the above equation, cost components are in the form of Eq. (2-24), e.g., initial cost.

$$C_{xj} = \int_{t_0}^{t_1} C_{ij} \cdot e^{\int_{t_0}^t \theta_i(\tau) d\tau} \cdot e^{-rt} \cdot dt \quad (2-24)$$

where  $C_{xj}$  is the  $x^{th}$  cost item of system  $j$ .

Equation (2-23) differs for different types of investors :

- 1) For the speculative builder, Eq. (2-23) becomes :

$$LCC = \sum_{j=1}^n C_{1j} \quad (2-25)$$

i.e., the builder is concerned solely with the minimization of initial costs.

TABLE (2-1)

UNIFORMAT COST BREAKDOWN

UNIFORMAT categories for building elements for recording or estimating costs of construction, repair, replacement, alteration, improvement, salvage.

| LEVEL I - SUBSYSTEMS             | LEVEL II - ELEMENTS  |
|----------------------------------|--|
| 01 FOUNDATIONS                   | 011 STANDARD FOUNDATIONS<br>012 SPECIAL FOUNDATION CONDITIONS                            |
| 02 SUBSTRUCTURE                  | 021 SLAB ON GRADE<br>022 BASEMENT EXCAVATION<br>023 BASEMENT WALLS                       |
| 03 SUPERSTRUCTURE                | 031 FLOOR CONSTRUCTION<br>032 ROOF CONSTRUCTION<br>033 STAIR CONSTRUCTION                |
| 04 EXTERIOR CLOSURE              | 041 EXTERIOR WALLS<br>042 EXTERIOR DOORS AND WINDOWS                                     |
| 05 ROOFING                       |  |
| 06 INTERIOR CONSTRUCTION         | 061 PARTITIONS<br>062 INTERIOR FINISHES<br>063 SPECIALTIES                               |
| 07 CONVEYING SYSTEMS             |  |
| 08 MECHANICAL SYSTEM             | 081 PLUMBING<br>082 HVAC<br>083 FIRE PROTECTION<br>084 SPECIAL MECHANICAL SYSTEMS        |
| 09 ELECTRICAL SYSTEMS            | 091 SERVICE AND DISTRIBUTION<br>092 LIGHTING AND POWER<br>093 SPECIAL ELECTRICAL SYSTEMS |
| 10 GENERAL CONDITIONS AND PROFIT |  |
| 11 EQUIPMENT                     | 111 FIXED AND MOVEABLE EQUIPMENT<br>112 FURNISHINGS<br>113 SPECIAL CONSTRUCTION          |
| 12 SITEWORK                      | 121 SITE PREPARATION<br>122 SITE IMPROVEMENT<br>123 SITE UTILITIES<br>124 OFF-SITE WORK  |

ii) Public investment : for a public investment ( $T = 0$ ),

Thus, Eq. (2-23), becomes :

$$LCC = \sum_{j=1}^n (C_{ij} + C_{oj} + C_{mj} + C_{rj} + C_{pj}) \quad (2-26)$$

For this case, future costs have the greatest importance and impact on life cycle cost (because of the no-tax situation).

iii) Private owner : for a private owner, Eq. (2-23) is the objective function. It can be seen that the impact of future costs on life cycle cost reduces, by increasing the tax rate.

In Eq. (2-23), the present worth of future cost items,  $C_o$ ,  $C_m$ ,  $C_r$ ,  $C_p$ , could be expressed as a product of some time function which is largely beyond our control and a base year cost which is a function of design; it can be significantly influenced by design decisions. Separating these two factors, and controlling the design, we can exert some control over the time factor. Thus, in general :

$$C_{xj} = C_{xj}^0 \cdot B_{xj} \quad (2-27)$$

in which :

$C_{xj} = f(\text{design, decisions})$  = Base year cost of operating,  
maintaining or repairing the  
system;

$B_{xj} = f(\text{time, inflation, discount rate})$  = present worth  
of time models  
for operating,  
maintenance or  
repair cost.

The time varying factors ( $B_{xj}$ ) could be shown more explicitly as  
a function of two factors (Fig. 2-5):

$$B = f(\theta, Z) \quad (2-28)$$

where :

$\theta$  = inflation

$Z$  = other factors, such as :

- a) base year cost change due to physical depreciation of  
the system, in terms of constant dollars;
- b) new regulations, e.g. new regulations requiring the use  
of only gas-fired heating in residential buildings (in-  
stead of fuel oil).

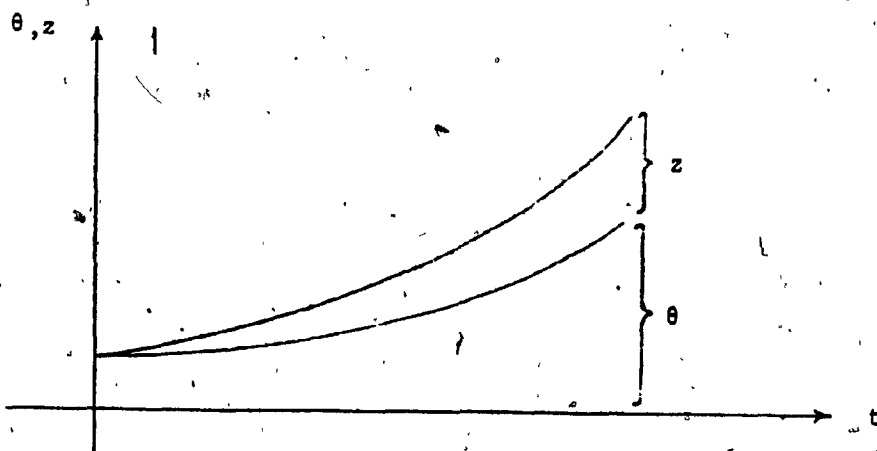


FIG. 2-5 - TIME VARYING FACTOR (B) COMPONENTS

The Z component is very difficult to calculate and to distinguish from inflation, except, in the presence of good records, which is seldom the case. In this study, only inflation effects have been considered, i.e.  $Z = 0$ , and thus  $B = f(\theta)$ .

Note : Because of the different nature of cash flows for repair and alteration costs, compared to operation and maintenance costs, they have different formulations for the time factor (B).

- i) For operating ( $B_o$ ), and maintenance ( $B_m$ ), the time factor has the form of :

$$B = \int_{t_1}^{t_E} e^{\int_0^t \theta(\tau) \cdot d\tau} \cdot e^{-rt} dt \quad (2-29)$$

using the inflation time model.

- ii) For repair ( $B_r$ ), and alteration ( $B_p$ ), the time factor has the form of (See Fig. 2-6) :

$$B = e^{(\theta-r) \cdot n} \frac{1 - e^{(t_E - n) \cdot (\theta-r)}}{1 - e^{(\theta-r) \cdot j}} \quad (2-30)$$

where :

$n$  = time from starting point to first repair;

$j$  = cycle of repair (i.e. a regular repair period has been assumed; and

$\theta$  = constant inflation rate.

Having the base year costs of repair and renewal, the future cost for each period can be computed. Fig. (2-6) shows the future periodic costs computed by using Eq. (2-30) and base year costs.

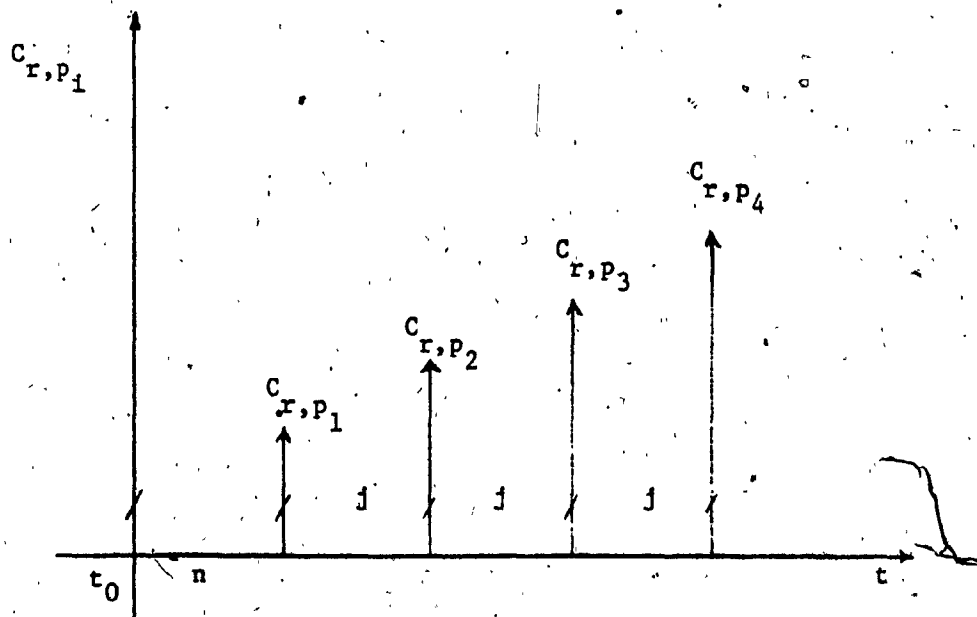


FIG. (2-6) - REPAIR AND ALTERATION CASH FLOW DIAGRAM



Finally, the life cycle cost relationship becomes :

$$LCC = \sum_{j=1}^n (C_{1j} + (1-T) (C_{0j}B_{0j} + C_{mj}B_{mj} + C_{rj}B_{rj} + C_{pj}B_{pj}) - T \cdot CCA_j) \quad (2-31)$$

## 2.5 TIME MODELLING

In the last section, a case was made for working in current dollars. Thus, we need to study the future behaviour of cash flows in order to determine time models for each component. One way to predict a suitable time model for a future cost item is to use past experience and statistical data. For example, for the energy component of the life cycle cost equation, time models can be developed for the different types of energy sources (fuel oil, Fig. (2-7); gas, Fig. (2-8); electricity, (Fig 2-9), by using published indices (Statistics Canada [7]). Models for other components can be developed from data found in BOMA [8] and IREM [9] reports.

In using past statistical data, one must be very careful about using models based on these data for predicting future costs. It is possible that different functions can fit almost perfectly the past data; however, depending on which function is selected, as represent-

ative of the future, Figs. (2-7, 2-8, 2-9), different design decisions will be made.

The above cost models can also be defined by their inflation models; figure (2-10) illustrates different types of inflation models for use in computing the B function; they include:

1. The linear inflation model ( $\theta = a$ ), which is constant over the period of study. This model is the one most commonly used in life-cycle costing studies.
2. Hyper-inflation models :
  - a)  $\theta = a + bt$  linearly increases with time.
  - b)  $\theta = a - bt$  linearly decreases with time.
3. Power inflation model.

$$\theta = \theta_e + (\theta_1 - \theta_e) e^{-d \cdot t}$$

where :

$a, b, d$  = constants (  $a$  is the same as  $\theta_1$  )

Cost models shown in Fig. (2-7, 2-8, 2-9) can all be defined by power inflation model.

$\theta_1$  = today's inflation rate

$\theta_e$  = predicted long-term inflation rate

$t$  = time from starting point of construction

The above-mentioned models are chosen for this work, but more work needs to be done in determining models which best fit the existing

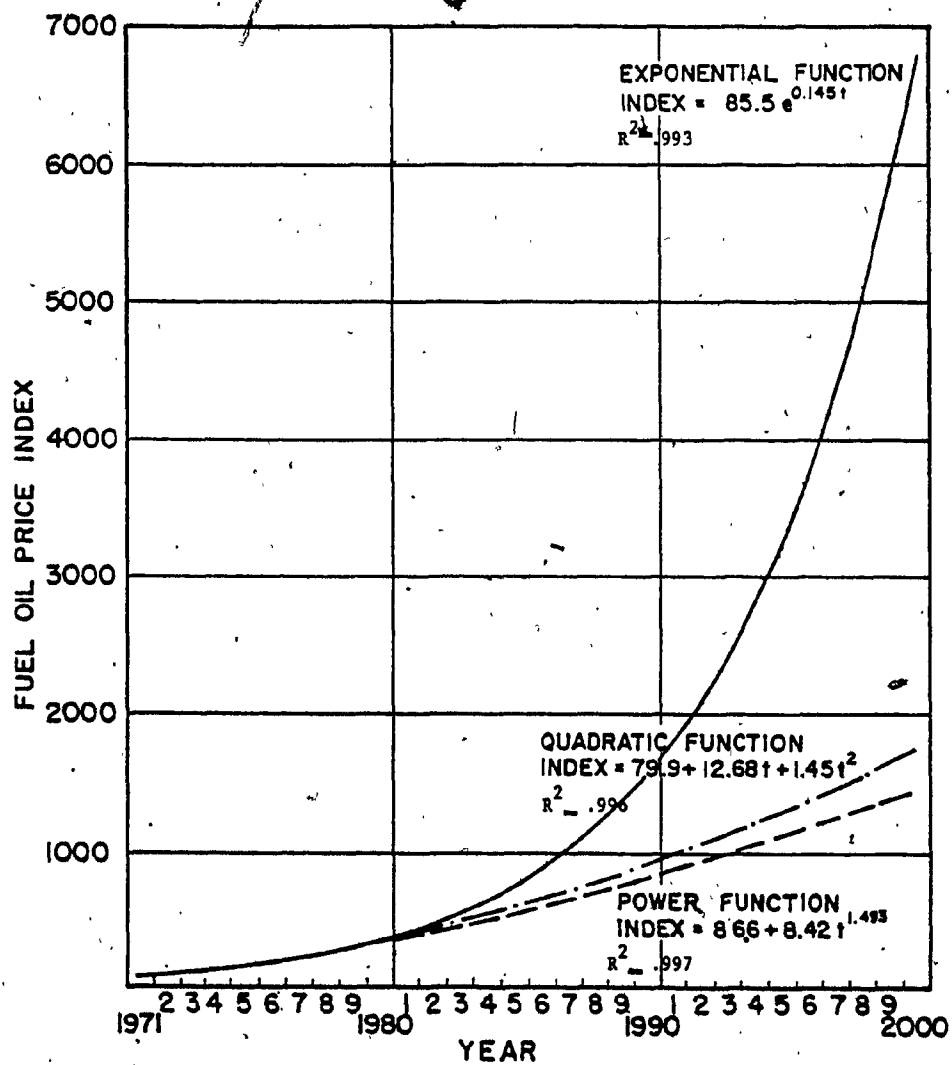


FIG. 2-7 - FUEL OIL TIME MODEL

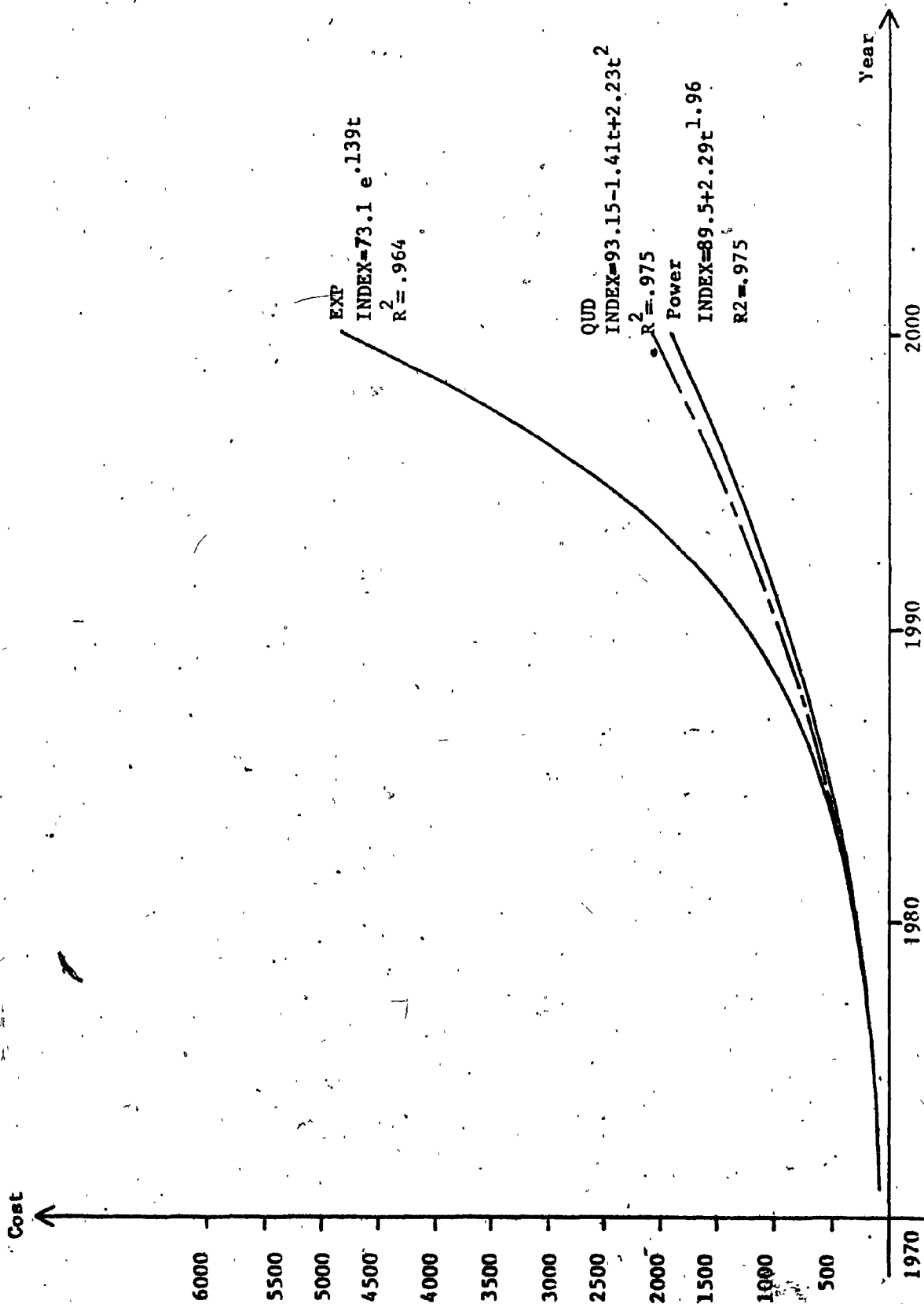


FIG. 2-8 GAS TIME, MODELS

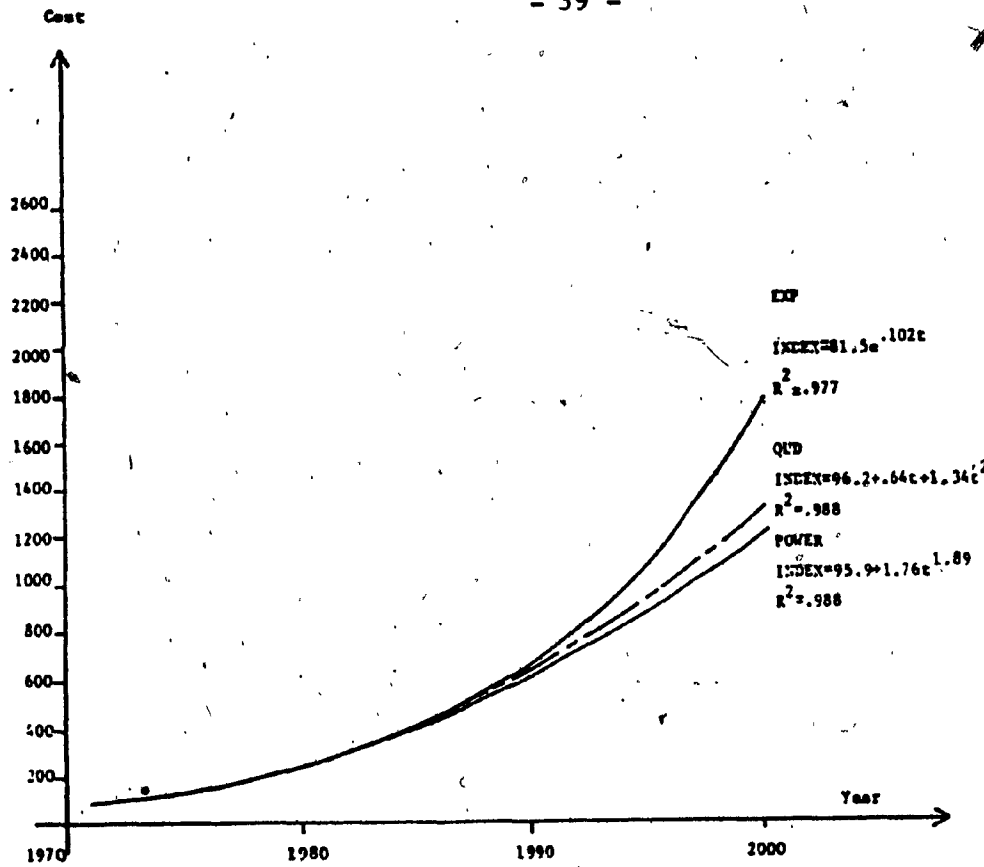


FIG. 2-9 - ELECTRICITY TIME MODELS

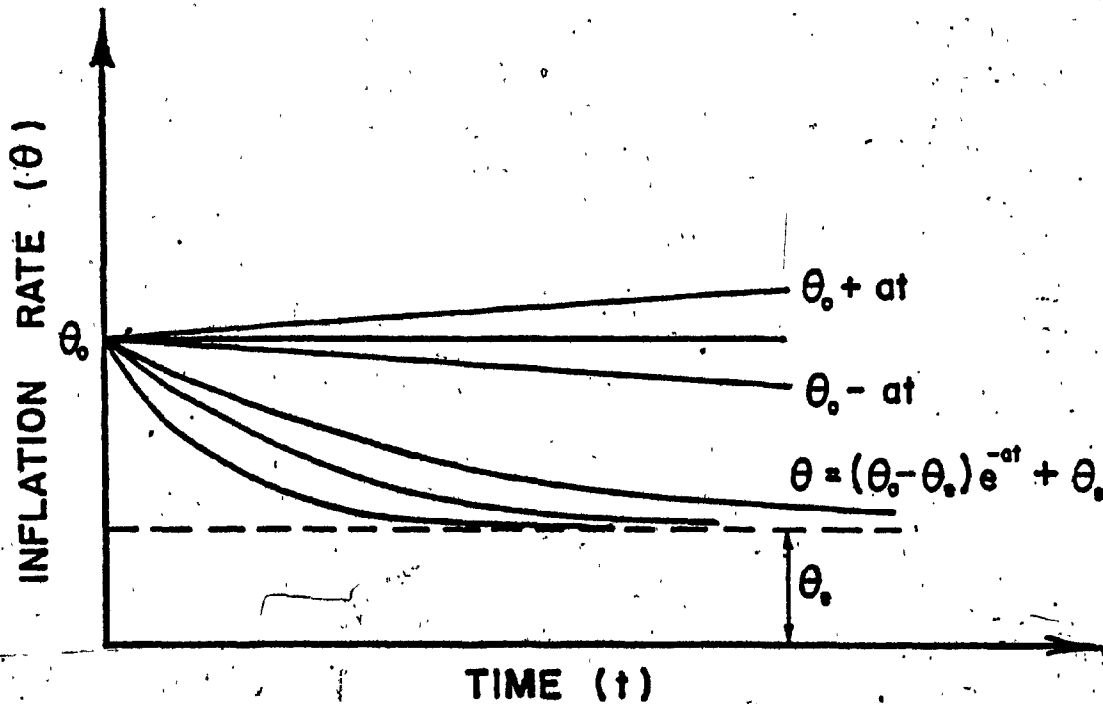


FIG. 2-10 - INFLATION MODELS

data, or forecast variations in future costs. This topic is a prime candidate for future research.

## 2.6 INFORMATION REQUIRED FOR LIFE CYCLE COST

In order to conduct a life-cycle cost study, the following steps are required :

1. Identify which building subsystems enter into the analysis at level I, (e.g. example, exterior closure and mechanical system).
2. Identify the level II elements for those subsystems which are identified in step 1, (e.g. considering the mechanical system, it could be plumbing, HVAC etc.).
3. Estimate the capital cost data for each element.
4. Determine the labour and resource expenses for proper operation and maintenance of each building subsystem or element (in today's dollars). The data for this section are very difficult to obtain, but some publications, such as BOMA reports [8] and Statistics Canada [7] can be helpful. Especially useful are data obtained from existing operations.
5. Forecast how the price of the labour and resource inputs for operating and maintenance and other costs are likely to vary with time (i.e., select appropriate time models and related parameters).

6. Estimate the nature and cost of future periodic repair and alteration work for each building element. It has to be determined when the first repair will occur and how often it will be repeated (Fig. 2-6). For innovative technologies, it is very difficult to estimate the cost, time and frequency of repairs.
7. Obtain from the client the after-tax rate,  $r$ , period of study  $t_e$ , and tax rate  $T$  to be used in the analysis.

## 2.7 INTERACTION BETWEEN DIFFERENT SUBSYSTEMS

One item of crucial importance in conducting a LCC analysis is properly accounting for interactions between capital cost and future costs, both with respect to individual building subsystems, and between different subsystems. When Eq. (2-31) is used, it is possible to miss some key interactions that result from design decisions. To aid in identifying interactions, it is useful to construct an interaction matrix (Fig. 2-11).

In a building system, interaction exists in different forms :

- i) between capital cost and future cost of subsystem  $i$ , e.g., in mechanical system by increasing the initial cost, the future operating cost can decrease;
- ii) between capital cost of subsystem  $i$  and future cost of system  $j$ , e.g., the interaction exists between capital cost of the enclosure system and the operating cost of the mechanical system;

- iii) between capital cost of subsystem i and capital cost of subsystem j, e.g., using a good system of enclosure might decrease the cost of the HVAC system; and
- iv) between future cost of subsystem i and future cost of subsystem j, e.g., by good maintenance of the building enclosure, we can save on energy cost of mechanical system.



| BUILDING SUBSYSTEM       | 01 FOUNDATIONS | 02 SUBSTRUCTURE | 03 SUPERSTRUCTURE | 04 EXTERIOR CLOSURE | 05 ROOFING | 06 INTERIOR CONSTRUCTION | 07 CONVEYING SYSTEM | 08 MECHANICAL SYSTEMS | 09 ELECTRICAL SYSTEM | 11 EQUIPMENT | 12 SITEWORK |
|--------------------------|----------------|-----------------|-------------------|---------------------|------------|--------------------------|---------------------|-----------------------|----------------------|--------------|-------------|
| 01 FOUNDATIONS           |                |                 |                   |                     |            |                          |                     |                       |                      |              |             |
| 02 SUBSTRUCTURE          |                |                 |                   |                     |            |                          |                     |                       |                      |              |             |
| 03 SUPERSTRUCTURE        |                |                 |                   |                     |            |                          |                     |                       |                      |              |             |
| 04 EXTERIOR CLOSURE      | ○              | ○               | ○                 |                     |            |                          |                     |                       |                      |              |             |
| 05 ROOFING               |                |                 |                   | ○                   |            |                          |                     |                       |                      |              |             |
| 06 INTERIOR CONSTRUCTION |                |                 |                   |                     | ○          |                          |                     |                       |                      |              |             |
| 07 CONVEYING SYSTEM      |                |                 |                   |                     |            | ○                        |                     |                       |                      |              |             |
| 08 MECHANICAL SYSTEMS    | ○              | ○               | ○                 | ●                   | ●          | ○                        |                     |                       |                      |              |             |
| 09 ELECTRICAL SYSTEM     |                |                 |                   | ●                   |            | ○                        |                     | ●                     |                      |              |             |
| 11 EQUIPMENT             |                |                 |                   |                     |            |                          |                     |                       |                      |              |             |
| 12 SITEWORK              |                |                 |                   |                     |            |                          |                     |                       |                      |              |             |

FIG. 2-11- INTERACTION MATRIX FOR ENERGY SYSTEM DESIGN

● INDICATES MAJOR INTERACTION  
○ INDICATES MINOR INTERACTION

## CHAPTER 3

A basic expression for life-cycle cost was presented in Chapter

2. In this chapter, the following topics will be treated :

1. identification of sources of uncertainty for the life cycle cost equation components;
2. demonstration of a practical method of measuring risk or uncertainty for each of these components;
3. exploration of how risk propagates in the life-cycle cost equation; and
4. determination of how risk may be incorporated into the decision-making process.

### 3.1 RISK SOURCES

In order to identify the risk sources in design and operation of buildings, one must analyze the building elements one-by-one (e.g. what are the risk sources in design and operation of the HVAC system?). Let us consider the life-cycle cost equation of building elements.

$$\begin{aligned} LCC_j &= C_{1j} + (1-T)(C_{0j}B_{0j} + C_{mj}B_{mj} + C_{rj}B_{rj} + C_{pj}B_{pj} - T.CCA_j) \\ &= C_{1j} (1-T.B_{Aj}) + (1-T)(C_{0j}B_{0j} + C_{mj}B_{mj} + C_{rj}B_{rj} + C_{pj}B_{pj}) \end{aligned} \quad (3-1a)$$

In the above equation,  $(1-T)$  and  $(1-T.B_{Aj})$  are assumed to be constant.

Assume that :

a)  $B_{1j} = (1-T.B_{Aj})$

b)  $(B_o, B_m, B_r) = (1-T) (B_o, B_m, B_r, B)$

in which the  $B$  values are tax adjusted values. Using these values, equation (3-1a) becomes :

$$\begin{aligned} LCC_j &= C_{ij}B_{ij} + C_{oj}B_{oj} + C_{mj}B_{mj} + C_{rj}B_{rj} + C_{pj}B_{pj} \\ &= \sum_{x=1}^5 C_{xj}B_{xj} \end{aligned} \quad (3-1)$$

where :

$C_{xj}$  = base year cost of building element  $j$  (capital, operating, maintenance, repair, alteration, etc.)

$B_{xj}$  = present worth of after-tax time variation models for building element  $j$ .

The uncertainty involved in base year costs ( $C_{xj}$ ) may be due to the following reasons :

1. inaccurate prediction routines, which because of simplicity, are frequently used, especially in the preliminary design phase;
2. uncertain productivity;
3. innovative technologies which are unproved to date;
4. complexity of design;
5. incomplete design information;
6. uncertain load variation (e.g. energy consumption);

The uncertainty involved in the determination of time models,  $(B_{xj})$  is due to :

1. lack of availability of data bank of past costs;
2. inability to predict future events which might affect future costs;
3. incomplete knowledge of the mechanisms which determine future costs;
4. changes in social trends which affect productivity;
5. unknown reliability of innovative technologies; and
6. retroactive legislation (e.g. regulation to use a minimum standard enclosure insulation).

Figure (3-1) demonstrates the uncertainty sources for different types of energy. Also, it demonstrates a hierarchy for decision making. It starts with the determination of availability of the energy type, and then considers the question of how stable is this availability. Stability depends on social, economic and political factors, and also on the export and import policies of each country. Finally, cost variations in the future must be identified. In this study, only the cost variation behaviour has been looked at. As noted previously, more work needs to be done in the future to assess future cost variations and to quantify the uncertainty relating to these variations.

### 3.2 MEASUREMENT OF RISK

Risk can be defined as the dispersion of the probability distribution of the performance measure being considered, e.g. the standard

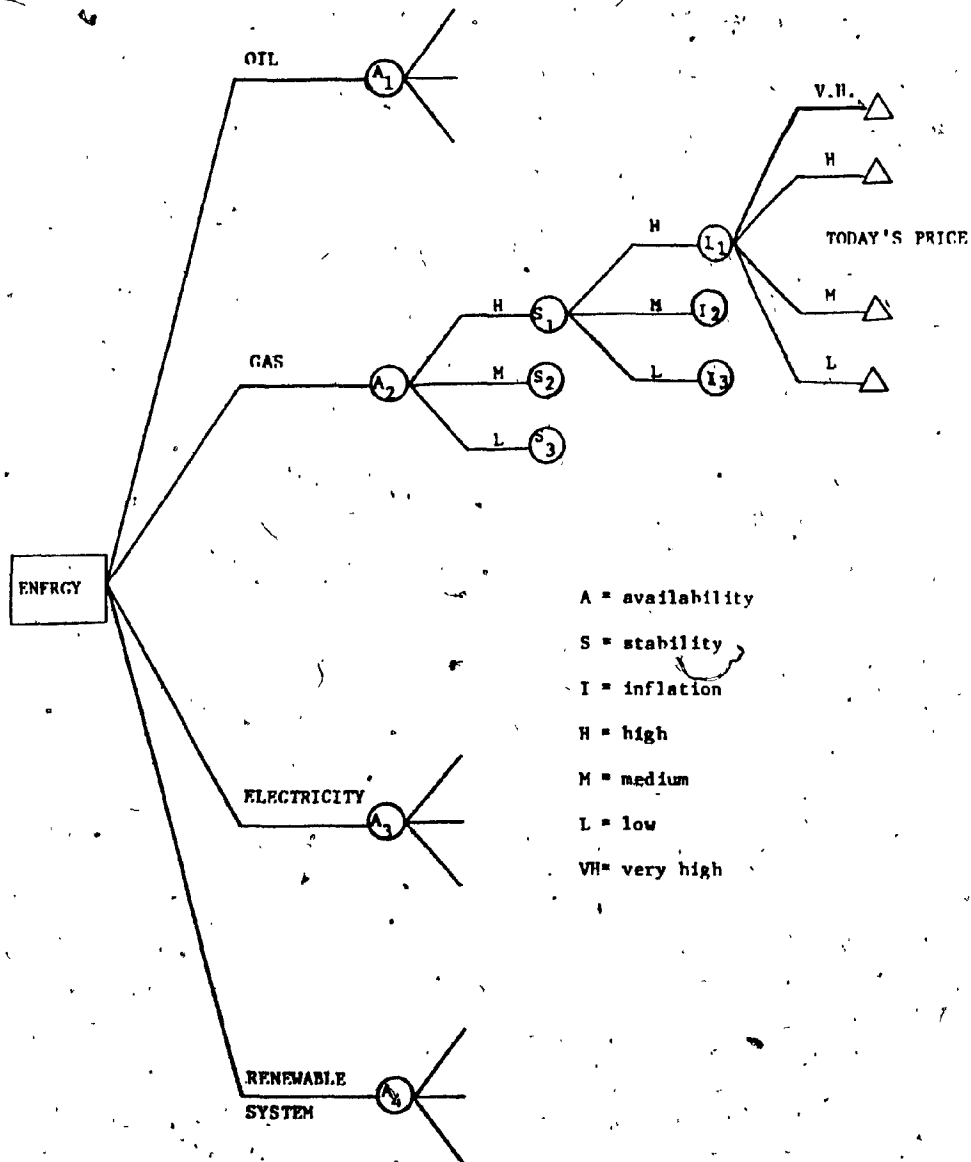


FIG. 3-1 - DETERMINATION OF ENERGY TYPE (DECISION TREE)

deviation of life-cycle cost (or relative coefficient of variation).

If we consider the life-cycle cost equation (3-1) :

$$LCC = \sum_{x=1}^5 C_{xj} B_{xj}$$

all the  $C_{xj}$  and  $B_{xj}$  are random variables which can be described by density functions. These variables, however, are complex functions of other variables, including design decisions, labour productivity, material quantities, wage rates, escalation rates, etc. (e.g.  $B = f(\theta)$ ), where  $\theta = \theta(t)$ .

In this study, the approach is to work with the aggregate variable  $C_{xj}$  in determining risk. For the  $B$  variable, we determine the uncertainty by estimating the uncertainty in the escalation models ( $\theta = \theta(t)$ ), and then deriving the uncertainty in  $B$  by applying fundamental statistical relations.

The goal here is to end up with a description of the uncertainty in life-cycle cost. This means we have to identify a method to represent the uncertainty.

#### 3.2.1 Density Function

This is the most rigorous manner in which to describe a random variable. Assuming sufficient information is available, measuring risk this way requires that probability density functions for each variable and joint distribution functions for each pair of variables must be estimated. Then we need some method to derive the density function for LCC, such as Monte Carlo simulation (11), (alternatively

we can make some specialized assumptions about the shape of the component density functions - e.g. they are all normal). The use of density functions is impractical, however, because of the lack of relevant data to derive density functions and because of the difficulty of generating the density function. For example, let us consider the general case of a multivariable random function :

$$Y = g(x_1, x_2, \dots, x_n) \quad (3-2)$$

Suppose we know the density functions  $f_{x_i}(x_i)$  for each of the  $x_i$  and the joint distributions between  $x_i$  and  $x_j$ ,  $f_{x_i x_j}(x_i, x_j)$  for all values of  $i, j$ . In theory, we can derive the density function  $f_Y(y)$ , but the problems are :

1. Each of the  $x_i$  are functions themselves for our case;
2. the information required for determining  $f_{x_i}(x_i)$  and  $f_{x_i x_j}(x_i, x_j)$  are very difficult to get.
3. the task of assembling them to determine  $f_Y(y)$  is difficult.

### 3.2.2 Moments

The moments of a random variable are defined as the expectations of the powers of the random variable which has a given distribution. If  $x$  is a random variable, the  $r^{\text{th}}$  moment of  $x$ , usually denoted by  $\mu_r'(x)$  is defined as :

$$\mu_r'(x) = E(x^r) \quad (3-3)$$

And the  $r^{\text{th}}$  central moment of  $x$  about  $\mu_r'(x)$  is denoted by [10] :

$$\mu_r''(x) = E[(x - \bar{x})^r] \quad (3-4)$$

In order to study the behaviour of random variables existing in eq. (3-1), we will use the first moment  $\bar{x}$  (mean), the second moment  $\mu_2''(x) = \sigma_x^2$  (variance) and preferably the third moment where  $\gamma_3$  is the coefficient of skewness  $\mu_3''(x) = \gamma_3 \sigma_x^3$ . Once we have the first, second and third moments for each variable, it is possible to approximate the moments for the B function and life-cycle cost in terms of the moments of the C's and B's by using a truncated Taylor series expansion.

For a single variable function:

$$Y = g(x) \quad (3-5)$$

using the first four terms of the Taylor series expansion about the mean value of  $x$ ,  $\bar{x}$ , we have:



$$Y = g(\bar{x}) + \left. \frac{dg}{dx} \right|_{\bar{x}} \cdot (x - \bar{x}) + \frac{1}{2} \left. \frac{d^2g}{dx^2} \right|_{\bar{x}} \cdot (x - \bar{x})^2 + \frac{1}{6} \left. \frac{d^3g}{dx^3} \right|_{\bar{x}} (x - \bar{x})^3 + \dots \quad (3-6)$$

Taking the expected value of both sides gives :

$$\bar{Y} = g(\bar{x}) + \left( \frac{1}{2} \cdot \left. \frac{d^2g}{dx^2} \right|_{\bar{x}} \sigma_x^2 + \left( \frac{1}{6} \cdot \left. \frac{d^3g}{dx^3} \right|_{\bar{x}} \gamma_3 \cdot \sigma_x^3 \right) \right) \quad (3-7)$$

where :

$\gamma_3$  is the coefficient of skewness

$\bar{Y}$  is the mean value of  $Y$

Using the definition of variance :

$$\sigma_x^2 = E(y - \bar{y})^2 \quad (3-8)$$

we get :

$$\begin{aligned} \sigma_y^2 = E(y - \bar{y})^2 &= \left( \frac{dg}{dx} \right)^2 \bigg|_{\bar{x}} \sigma_x^2 + \left( \frac{dg}{dx} \cdot \frac{d^2g}{dx^2} \right) \bigg|_{\bar{x}} \gamma_3 \sigma_x^3 \\ &+ \left( \frac{1}{3} \cdot \frac{dg}{dx} \cdot \frac{d^3g}{dx^3} \right) \bigg|_{\bar{x}} \gamma_4 \sigma_x^4 - \left( \frac{1}{6} \cdot \frac{d^2g}{dx^2} \cdot \frac{d^3g}{dx^3} \right) \bigg|_{\bar{x}} \\ &(2 \cdot \gamma_5 \cdot \sigma_x^5) + \dots \end{aligned} \quad (3-9)$$

And the third moment can be approximated from:

$$\begin{aligned} \mu_3'(y) = E(y - \bar{y})^3 &= \left( \frac{dg}{dx} \right)^3 \bigg|_{\bar{x}} \gamma_3 \sigma_x^3 + \left( \frac{3}{2} \cdot \left( \frac{dg}{dx} \right)^2 \cdot \frac{d^2g}{dx^2} \right) \bigg|_{\bar{x}} \gamma_4 \sigma_x^4 \\ &- \left( \frac{3}{4} \cdot \frac{dg}{dx} \cdot \left( \frac{d^2g}{dx^2} \right)^2 \right) \bigg|_{\bar{x}} (\gamma_5 - 2\gamma_3) \sigma_x^5 + \left( \frac{1}{2} \cdot \left( \frac{dg}{dx} \right)^2 \cdot \frac{d^3g}{dx^3} \right) \bigg|_{\bar{x}} \\ &(\gamma_5 - \gamma_3) \sigma_x^5 + \left( \frac{1}{12} \cdot \frac{dg}{dx} \cdot \left( \frac{d^3g}{dx^3} \right)^2 \right) \bigg|_{\bar{x}} \gamma_7 \sigma_x^7 + \left( \frac{1}{8} \cdot \left( \frac{d^2g}{dx^2} \right)^2 \cdot \frac{d^3g}{dx^3} \right) \bigg|_{\bar{x}} \\ &(\gamma_7 + \gamma_3 + 2) \sigma_x^7 + \left( \frac{1}{24} \cdot \frac{d^2g}{dx^2} \cdot \left( \frac{d^3g}{dx^3} \right)^2 \right) \bigg|_{\bar{x}} (\gamma_8 - \gamma_3^2) \sigma_x^8 \end{aligned} \quad (3-10)$$

where :

$\gamma_n$  is the coefficient of  $n^{\text{th}}$  moment.

$$\gamma_n = \frac{\mu_n'(x)}{\sigma_x^n} \quad (3-11)$$

e.g. coefficient of skewness  $\gamma_3$  and coefficient of peakedness :

( $\gamma_4$ )

Now let us consider the multi-variable case:

$$Y = g(x_1, x_2, \dots, x_n) \quad (3-12)$$

Using the Taylor series expansion, we will have:

$$\begin{aligned} Y = g(\bar{x}_1, \bar{x}_2, \dots, \bar{x}_n) &+ \sum_{i=1}^n \frac{\partial g(x_1, x_2, \dots, x_n)}{\partial x_i} \bigg|_{\bar{x}} (x_i - \bar{x}_i) \\ &+ \frac{1}{2} \left[ \sum_{i=1}^n \frac{\partial^2 g(x_1, x_2, \dots, x_n)}{\partial x_i^2} \bigg|_{\bar{x}} (x_i - \bar{x}_i)^2 \right. \\ &\left. + 2 \sum_{i < j}^n \sum_j \frac{\partial^2 g(x_1, x_2, \dots, x_n)}{\partial x_i \partial x_j} \bigg|_{\bar{x}} (x_i - \bar{x}_i) (x_j - \bar{x}_j) \right] + \dots \end{aligned}$$

(3-13)

The moments for this function are [11]:

$$\begin{aligned} \bar{Y} = g(\bar{x}_1, \bar{x}_2, \dots, \bar{x}_n) &+ \frac{1}{2} \left\{ \sum_{i=1}^n \frac{\partial^2 g(x_1, x_2, \dots, x_n)}{\partial x_i^2} \bigg|_{\bar{x}} \sigma_i^2 \right. \\ &\left. + 2 \sum_{i < j}^n \sum_j \frac{\partial^2 g(x_1, x_2, \dots, x_n)}{\partial x_i \partial x_j} \bigg|_{\bar{x}} \cdot E[(x_i - \bar{x}_i) (x_j - \bar{x}_j)] \right\} + \dots \end{aligned}$$

(3-14)

$$\begin{aligned}
 \sigma_y^2 &= \sum_{i=1}^n \left[ \frac{\partial g(x_1, x_2, \dots, x_n)}{\partial x_i} \right]_{\bar{x}}^2 \sigma_i^2 \\
 &+ 2 \sum_{i=1}^n \sum_{j=1, j \neq i}^n \frac{\partial g(x_1, x_2, \dots, x_n)}{\partial x_i} \left[ \frac{\partial g(x_1, x_2, \dots, x_n)}{\partial x_j} \right]_{\bar{x}} E[(x_i - \bar{x}_i)(x_j - \bar{x}_j)] \\
 &+ \sum_{i=j}^n \frac{\partial g(x_1, x_2, \dots, x_n)}{\partial x_i} \left[ \frac{\partial^2 g(x_1, x_2, \dots, x_n)}{\partial x_i^2} \right]_{\bar{x}} \gamma_{3i} \sigma_i^3 \\
 &+ \sum_{i=1}^n \sum_{j=1, j \neq i}^n \left\{ \frac{\partial g(x_1, x_2, \dots, x_n)}{\partial x_i} \left[ \frac{\partial^2 g(x_1, x_2, \dots, x_n)}{\partial x_j^2} \right]_{\bar{x}} E[(x_i - \bar{x}_i)(x_j - \bar{x}_j)^2] \right\} \\
 &+ 2 \sum_{i=1}^n \sum_{j=1, j \neq i}^n \left\{ \frac{\partial g(x_1, x_2, \dots, x_n)}{\partial x_i} \left[ \frac{\partial^2 g(x_1, x_2, \dots, x_n)}{\partial x_i \partial x_j} \right]_{\bar{x}} E[(x_i - \bar{x}_i)^2 (x_j - \bar{x}_j)] \right\} \\
 &+ 2 \sum_{i=1}^n \sum_{j=1, j \neq i}^n \sum_{k=1, k \neq j}^n \left\{ \frac{\partial g(x_1, x_2, \dots, x_n)}{\partial x_i} \left[ \frac{\partial^2 g(x_1, x_2, \dots, x_n)}{\partial x_j \partial x_k} \right]_{\bar{x}} E[(x_i - \bar{x}_i)(x_j - \bar{x}_j)(x_k - \bar{x}_k)] \right\}
 \end{aligned}
 \tag{3-15}$$

$$\begin{aligned}
 \mu_3(y) = & \sum_{i=1}^n \left[ \frac{\partial g(x_1, x_2, \dots, x_n)}{\partial x_i} \right]_{\bar{x}}^3 \gamma_{3i} \sigma_i^3 \\
 & + 3 \sum_{\substack{i,j \\ i \neq j}}^n \sum_{\substack{i,j \\ i \neq j}}^n \left\{ \left[ \frac{\partial g(x_1, x_2, \dots, x_n)}{\partial x_i} \right]_{\bar{x}}^2 \frac{\partial g(x_1, x_2, \dots, x_n)}{\partial x_j} \right. \\
 & \quad \left. E[(x_i - \bar{x}_i)^2 (x_j - \bar{x}_j)] \right\} \\
 & + 6 \sum_{\substack{i,j,k \\ i < j < k}}^n \sum_{\substack{i,j,k \\ i < j < k}}^n \left\{ \left[ \frac{\partial g(x_1, x_2, \dots, x_n)}{\partial x_i} \right]_{\bar{x}} \left[ \frac{\partial g(x_1, x_2, \dots, x_n)}{\partial x_j} \right]_{\bar{x}} \right. \\
 & \quad \left. \frac{\partial g(x_1, x_2, \dots, x_n)}{\partial x_k} \right]_{\bar{x}} E[(x_i - \bar{x}_i)(x_j - \bar{x}_j)(x_k - \bar{x}_k)] \}
 \end{aligned}
 \tag{3.16}$$

Information required for determination of approximate moments with the above-mentioned degree of accuracy (only four terms of Taylor series expansion), are impossible to gather. Some information, like moments (beyond fourth moment), do not have a ready physical interpretation. Even more, in order to use the third moment, we have to find higher moments of  $x_i$ 's. Hence, for practical purposes, most of the terms are eliminated and only the first and second moments (mean and variance) will be used in the analysis.

For example, consider the B function:

$$B = (1-T) \cdot \int_{t_1}^{t_E} (e^{\theta t} \cdot e^{-rt}) dt$$

$$= (1-T) \left[ \frac{1}{\bar{\theta}-r} (e^{(\bar{\theta}-r)t_E} - e^{(\bar{\theta}-r)t_1}) \right] \quad (3-17)$$

$$E(B) = (1-T) \left[ \frac{1}{\bar{\theta}-r} (e^{(\bar{\theta}-r)t_E} - e^{(\bar{\theta}-r)t_1}) + \right.$$

$$\left. \left( \frac{1}{2} \right) \left( \frac{1}{\bar{\theta}-r} \right) (t_E^2 e^{(\bar{\theta}-r)t_E} - t_1^2 e^{(\bar{\theta}-r)t_1}) - \right.$$

$$\left. \frac{2}{(\bar{\theta}-r)^2} (t_E e^{(\bar{\theta}-r)t_E} - t_1 e^{(\bar{\theta}-r)t_1}) + \right.$$

$$\left. \frac{2}{(\bar{\theta}-r)^3} (e^{(\bar{\theta}-r)t_E} - e^{(\bar{\theta}-r)t_1}) \sigma_\theta^2 \right] \quad (3-18)$$

$$\sigma^2(B) = (1-T)^2 \left[ \frac{1}{\bar{\theta}-r} (t_E e^{(\bar{\theta}-r)t_E} - t_1 e^{(\bar{\theta}-r)t_1}) - \right.$$

$$\left. \frac{1}{(\bar{\theta}-r)^2} (t_E^2 e^{(\bar{\theta}-r)t_E} - t_1^2 e^{(\bar{\theta}-r)t_1}) + \sigma_\theta^2 \right] \quad (3-19)$$

In order to examine the significance of omitting higher order terms in equations (3-17, 3-18, 3-19), several studies were made.

a) Consider mean and variance only, as variance or coefficient of variation increases, the mean value increases exponentially. Figs. (3-2a , 3-2b , 3-2c ) demonstrate the effect of variance on mean value ( $\gamma_3=0$ ). (Each figure demonstrates a specific value of  $(\theta-r)$ ;

b) Consider mean, variance and coefficient of skewness ( $\gamma_3$ ), as positive values, for  $\gamma_3$  increases, the mean value increases exponentially. Figs. (3-2a,3-2b,3-2c ), demonstrate the effect of different coefficients of skewness ( $-3 \leq \gamma_3 \leq +3$ ) for different values of  $(\theta - r)$ . For negative values of  $\gamma_3$ , the mean values partially decrease (when the coefficient of variation is high). By ignoring high coefficient of skewness in an uncertain decision-making environment, one might make wrong decisions based on wrong mean value. In order to incorporate the coefficient of skewness or high order moments, they can be computed by using basic data (Max, Min and mean values) and triangular approximation of density functions.

In this study, no work has been done in computing high order moments, and as defined in Eqs. (3-17, 3-18, 3-19), for risk analysis purposes, only first and second moments are used.

The information required for first and second moment calculations are the mean value and coefficient of variation (the coefficient of variation can be calculated by dividing the second moment by the first moment of the variable) for each basic variable; for example " $\theta$ " or

"C".

To calculate the mean and variance of life-cycle cost, the following procedure is suggested :

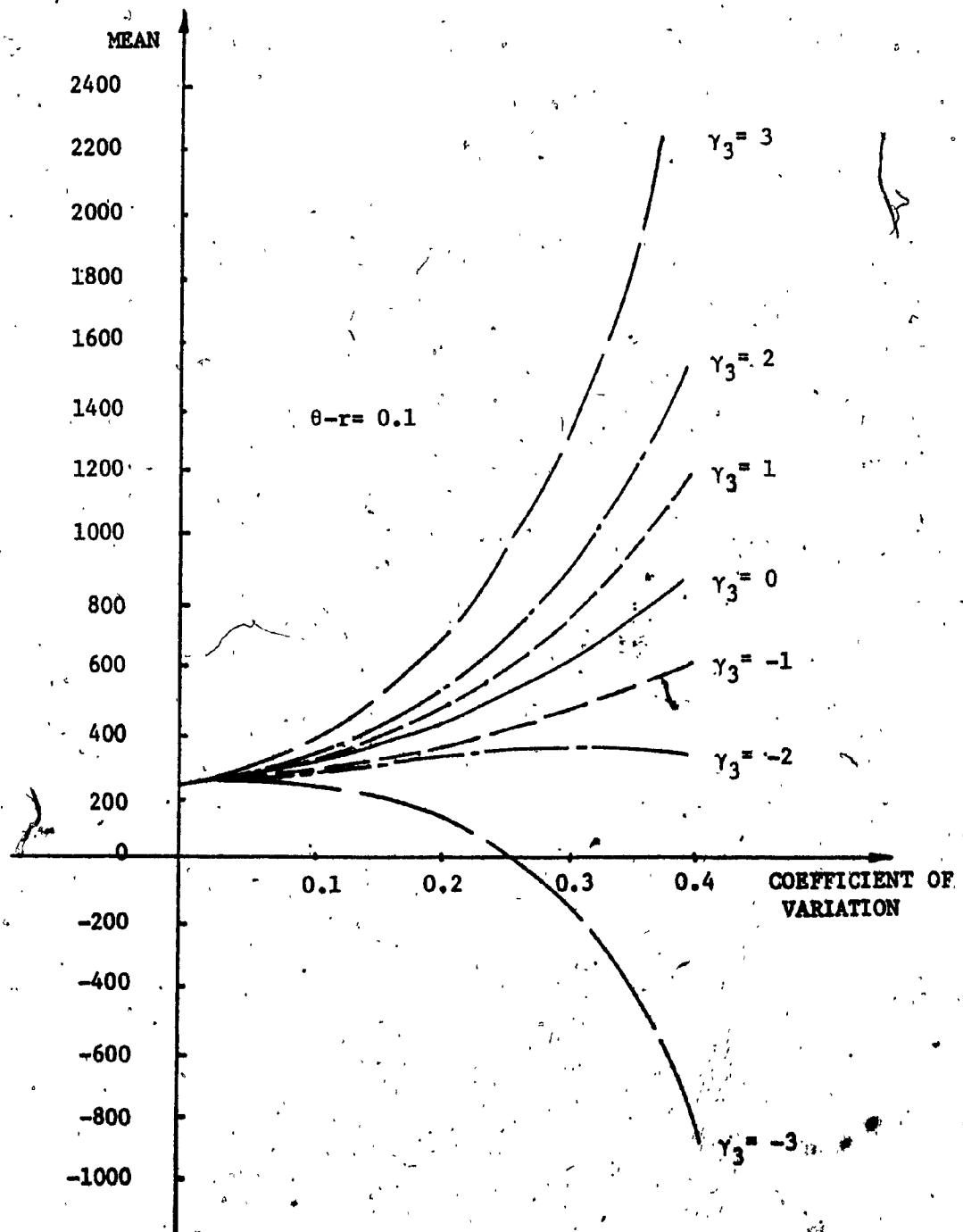


FIG. 3-2a - VARIATION OF MEAN AS A FUNCTION OF COEFFICIENT OF VARIATION AND  $\gamma_3$ .



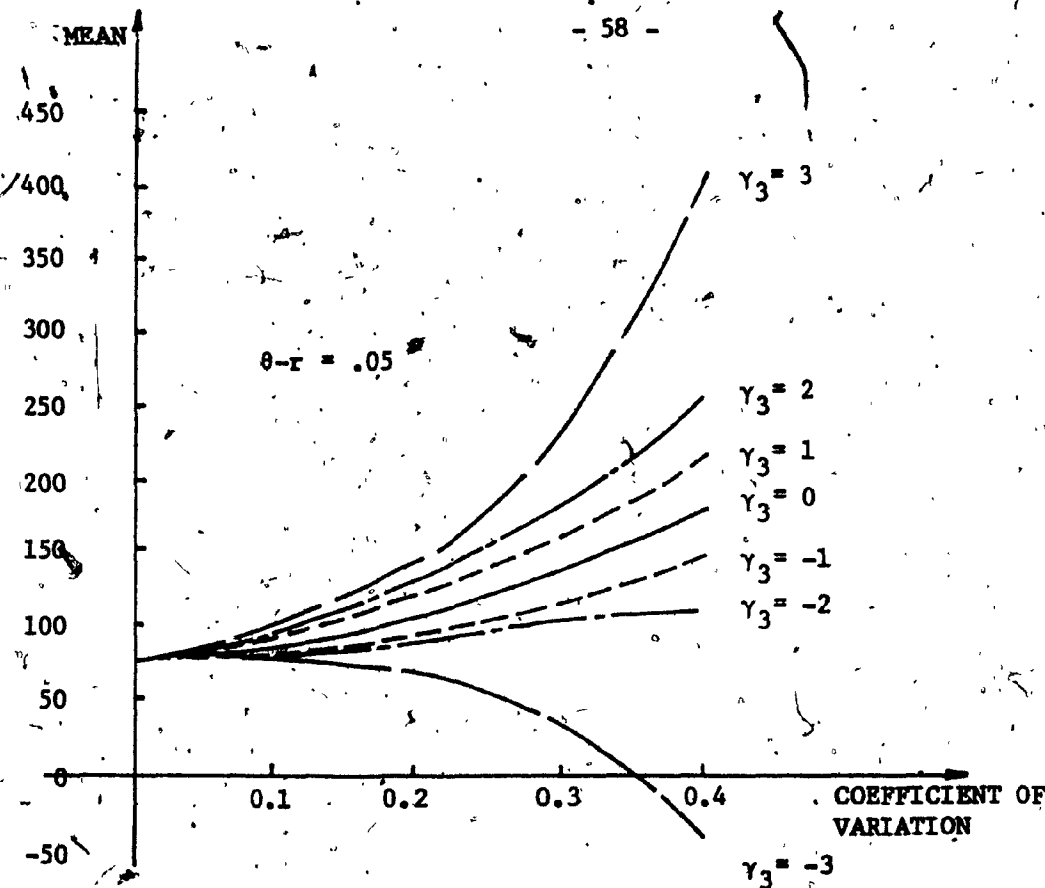


FIG. 3-2b - VARIATION OF MEAN AS A FUNCTION OF COEFFICIENT OF VARIATION AND  $\gamma_3$ .

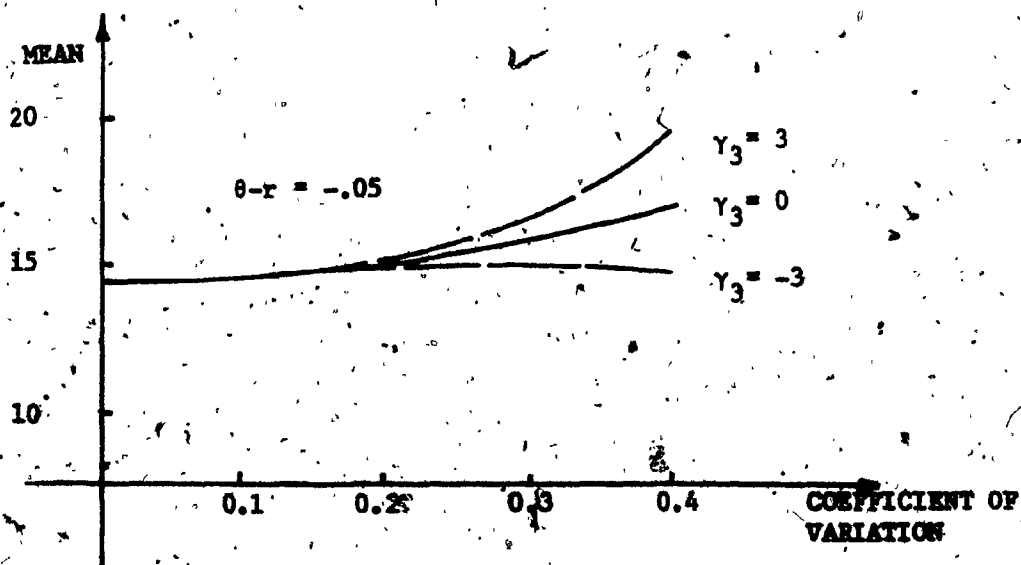


FIG. 3-2c - VARIATION OF MEAN AS A FUNCTION OF COEFFICIENT OF VARIATION AND  $\gamma_3$ .

1. Estimate the capital cost, base year costs for future components of LCC and the related coefficient of variation. For example, capital cost of HVAC system is, \$3,000,000 and its coefficient of variation  $\frac{\sigma_x}{\bar{x}}$  is .025. For greatest accuracy, the analysis must start at the lowest level. For example, considering Fig. (3-3), one must do the estimation at the component level in order to accurately estimate the uncertainty.
2. Identify the inflation scenario for each future cost component and its related coefficient of variation. For example,  $\theta = 15\%$  and varies by  $\sigma_{\theta/\theta} = .3$
3. Using the simple form of eqs. (3-7, 3-8), i.e. :

$$Y = g(\bar{x}) + 1/2 \left( \frac{d^2g}{dx^2} \bigg|_{\bar{x}} \right) \sigma_x^2 \quad (3-20)$$

$$\sigma_Y^2 = \left( \frac{dg}{dx} \bigg|_{\bar{x}} \right)^2 \sigma_x^2 \quad (3-21)$$

Compute the mean and variance of B.

Note : The B function could be treated in three different ways :

- a)  $B = f(\theta)$ , where  $\theta$  could be one of the inflation models described in Chapter 2 and  $\theta$  is assumed to be known with certainty.
- b)  $B = f(\theta)$ , where  $\theta$  is time dependent with some coefficient of variation. Using eqs. (3-21, 3-22), the mean and variance of B can be obtained.

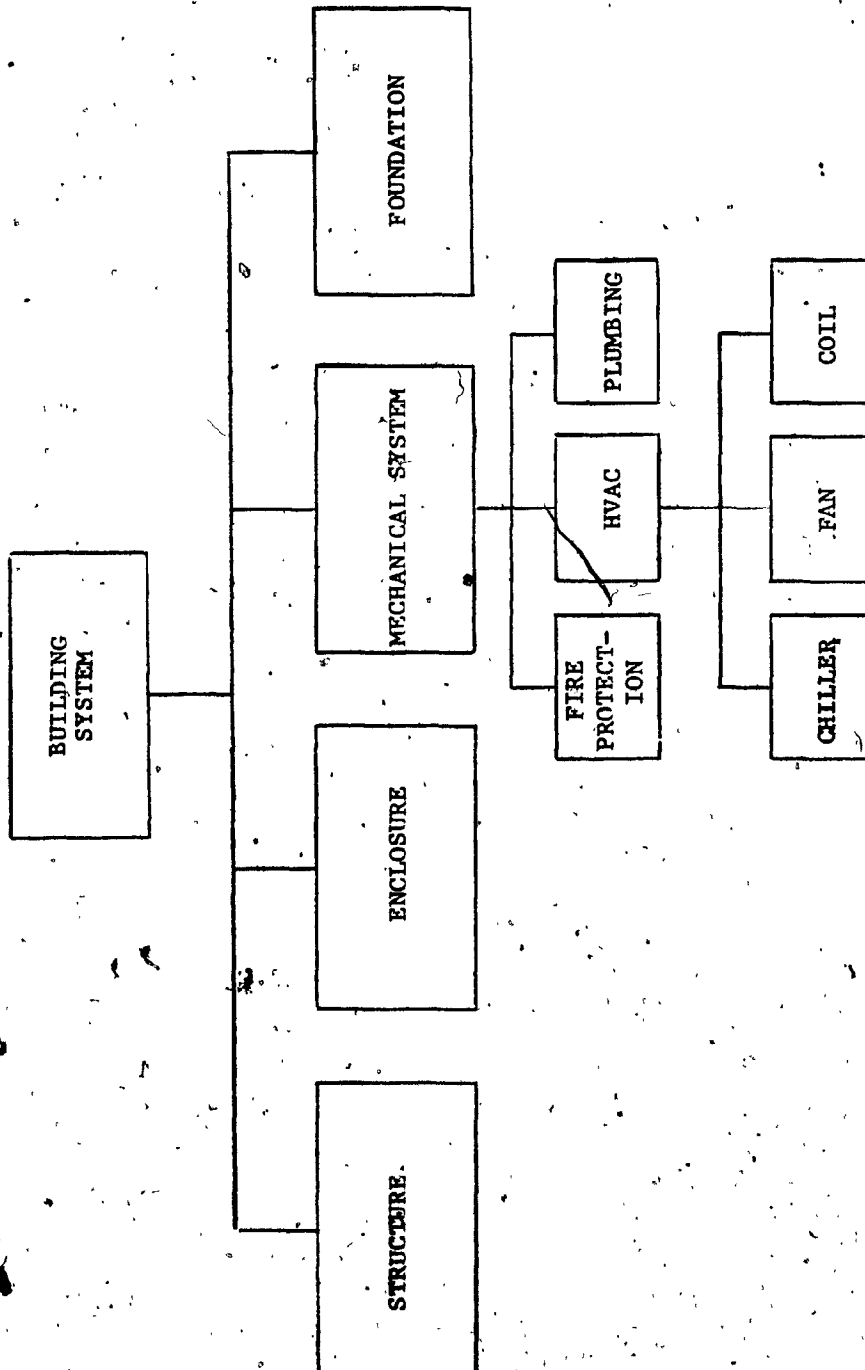


FIG. 3-3 -BUILDING SYSTEM BREAKDOWN

c)  $B = f(\theta)$ , where  $\theta$  is a combination of several models, where each one has a specified probability of occurrence. For example,  $\theta_1 = 10\%$ ;  $P_1 = .4$ ;  $\theta_2 = 5\%$ ;  $P_2 = .3$ ;  $\theta_3 = 20\%$ ;  $P_3 = .3$ . For each inflation model, the corresponding  $B$  must be evaluated :

$$B_1 = B(\theta_1); B_2 = B(\theta_2); B_3 = B(\theta_3) \quad (3-21)$$

then,

$$\bar{B} = \sum_{i=1}^3 p_i B_i \quad (3-22)$$

and

$$\sigma_B^2 = \sum_{i=1}^3 p_i (B_i - \bar{B})^2 \quad (3-23)$$

In this case, the high order moments also can be computed. For example, coefficients of skewness can be computed as :

$$\mu_3(B) = \sum_{i=1}^3 p_i (B_i - \bar{B})^3$$

4. Compute the moments of life-cycle cost.

Take the general life-cycle cost equation :

$$LCC = \sum_{j=1}^n (C_{1j} B_{1j} + C_{0j} B_{0j} + C_{mj} B_{mj} + C_{rj} B_{rj} + C_{pj} B_{pj})$$

Equation (3-23) consists of some deterministic terms and some probabilistic terms. For example,  $B_{ij}$  is deterministic. The remaining terms are all random variables, and uncertainty is greatest for future costs.

Take the case of product terms, e.g.  $C_{oj} B_{oj}$ . These two factors for most of the subsystems are correlated, but for the moment assume that they are not correlated; then:

$$E [ C_{oj} B_{oj} ] = \bar{C}_{oj} \bar{B}_{oj} \quad (3-25)$$

and

$$\sigma^2 [C_{oj} B_{oj}] = \bar{C}_{oj}^2 \sigma_{B_{oj}}^2 + \bar{B}_{oj}^2 \sigma_{C_{oj}}^2 + \sigma_{C_{oj}}^2 \sigma_{B_{oj}}^2 \quad (3-26)$$

Equation (3-26) shows how risk spreads, also how time component variations can increase the risk, even though base year costs are known with a relatively higher degree of certainty. For example, uncertainty involved in operating cost of HVAC systems dominates the initial cost uncertainty and controls overall risk level.

Once we have the first and second moments for the product terms in the life-cycle cost equation, then:

$$E(LCC) = \overline{LCC} = \sum_{j=1}^m C_{ij} B_{ij} + C_{oj} B_{oj} + C_{mj} B_{mj} + C_{rj} B_{rj} + C_{pj} B_{pj}$$

(3-27)

and variance:

$$\begin{aligned} \sigma^2 LCC = & \sum_{j=1}^m (B_{ij})^2 \sigma^2 C_{ij} + \overline{C}_{oj}^2 \sigma^2 B_{oj} + \overline{B}_{oj}^2 \sigma^2 C_{oj} \\ & + \sigma^2 C_{oj} \sigma^2 B_{oj} + \overline{C}_{mj}^2 \sigma^2 B_{mj} + \overline{B}_{mj}^2 \sigma^2 C_{mj} + \sigma^2 C_{mj} \sigma^2 B_{mj} \\ & + \overline{C}_{rj}^2 \sigma^2 B_{rj} + \overline{B}_{rj}^2 \sigma^2 C_{rj} + \sigma^2 C_{rj} \sigma^2 B_{rj} + \overline{C}_{pj}^2 \sigma^2 B_{pj} \\ & + \overline{B}_{pj}^2 \sigma^2 C_{pj} + \sigma^2 B_{pj} \sigma^2 C_{pj} \\ & + 2 \sum_{j=1}^m \sum_{k=j+1}^m ((B_{ij})(B_{ik})) \text{Cov}[C_{ij}, C_{ik}] \\ & + [\text{Cov}[O_j, O_k] + \text{Cov}[M_j, M_k] + \text{Cov}[R_j, R_k] \\ & + \text{Cov}[P_j, P_k] \\ & + 2 \sum_{j=1}^m \sum_{k=j+1}^m (B_{ij}) [\text{Cov}[C_{ij}, O_k] + \\ & \text{Cov}[C_{ij}, M_k] + \text{Cov}[C_{ij}, R_k] + \text{Cov}[C_{ij}, P_k]] + \end{aligned}$$

$$\begin{aligned} & \text{Cov}[O_j, M_k] + \text{Cov}[O_j, R_k] \\ & + \text{Cov}[O_j, P_k] + \\ & \text{Cov}[M_j, R_j] + \text{Cov}[M_j, P_j] + \text{Cov}[R_j, P_j] \end{aligned}$$

(3-28)

in which:

$$O_j = C_{oj} \cdot B_{oj}$$

$$M_j = C_{mj} \cdot B_{mj}$$

$$R_j = C_{rj} \cdot B_{rj}$$

$$P_j = C_{pj} \cdot B_{pj}$$

$O_j, M_j, R_j, P_j$  are functions of other variables, where those variables themselves are functions of other variables.

From Benjamin and Cornell [12], the covariance between two functions  $Y_1$  and  $Y_2$  where :

$$Y_1 = g_1(x_1, x_2, \dots, x_n) \quad (3-29)$$

and

$$Y_2 = g_2(x_1, x_2, \dots, x_n)$$

is given by :

$$\text{Cov}[Y_1, Y_2] = \sum_{i=1}^n \sum_{j=1}^n \frac{\partial Y_1}{\partial x_i} \bigg|_{\bar{x}} \frac{\partial Y_2}{\partial x_j} \bigg|_{\bar{x}} \text{Cov}(x_i, x_j) \quad (3-30)$$

For example for  $O_j, O_k$ ,  $\text{Cov}(O_j, O_k)$  is given by :

$$\begin{aligned} \text{Cov}(O_j, O_k) = & B_{Oj}[B_{Ok} \cdot \text{Cov}[C_{Oj}, C_{Ok}] + C_{Ok} \cdot \text{Cov}[C_{Oj}, B_{Ok}]] \\ & + C_{Oj}[B_{Ok} \cdot \text{Cov}[B_{Oj}, C_{Ok}] + C_{Ok} \text{Cov}[B_{Oj}, B_{Ok}]] \quad (3-31) \end{aligned}$$

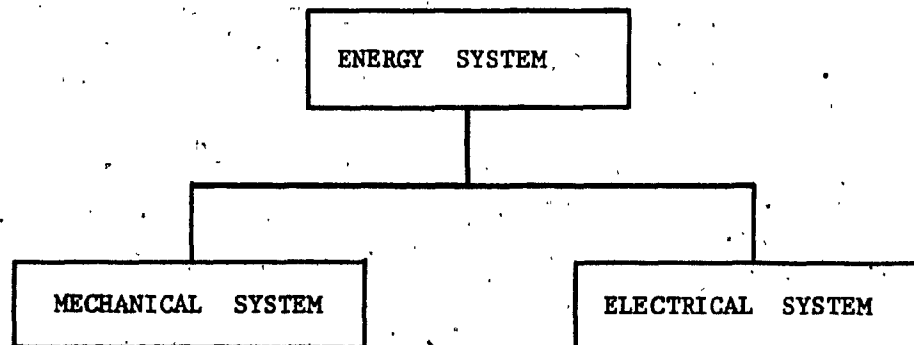
Some of these covariances are zero (no correlation). For example, consider the various mechanical subsystems elements. A correlation exists between operating cost time models, but rarely is there a correlation between base years costs and time models; therefore, the covariance between  $C_{Oj}$  and  $B_{Oj}$  in most cases is zero.



The above approach to risk analysis has been incorporated into a computer program, which can easily be used in the design office.

To illustrate the use of the foregoing relationships, consider the following example.

Calculate the LCC cost and risk for a two-component system (mechanical and electrical system), having zero tax rate, 1.5 year ( $t_1$ ) construction period, 30 years study period ( $t_E$ ) and MARR ( $r$ ) of 14%. Detailed cost data for each system are given as follows:



1. Mechanical System :

$$\begin{array}{ll} C_1 = \$10,000 & \sigma_{C_1} = \$250 \\ C_0 = 1,000 & \sigma_{C_0} = 100 \\ \theta = 15\% & \sigma_{\theta} = 4.5\% \end{array}$$

2. Electrical System :

$$\begin{array}{ll} C_1 = \$ 5,000 & \sigma_{C_1} = \$500 \\ C_0 = 750 & \sigma_{C_0} = 75 \\ \theta = 10\% & \sigma_{\theta} = 3\% \end{array}$$

LCC analysis of mechanical system:

- 1) Compute  $B_M$

$$B = f(\theta) = \int_{t_1}^{t_E} e^{(\theta-r)} dt$$

using Eq. (3-18, 3-19)

$$\bar{B} = 48.9, \sigma_B = 27.57$$

- 2) Compute  $\overline{LCC}_M$

$$\overline{LCC} = \bar{C}_1 + (1-T) \cdot \bar{C}_0 \bar{B}_0 - T \cdot \overline{CCA}$$

$$T = 0, \overline{LCC} = \bar{C}_1 + \bar{C}_0 \bar{B}_0$$

$$\overline{LCC}_M = 10,000 + 1,000 \cdot (48.9) = \$58,900$$

- 3) Compute the variance of LCC,  $\sigma^2_{LCC}$

$$\begin{aligned} \sigma^2_{LCC_M} &= (250)^2 + (100)^2 (48.9)^2 + (1000)^2 (27.57)^2 + (100)^2 (25.57)^2 \\ &= (18,118)^2 \end{aligned}$$

LCC analysis of electrical system:

- 1) Compute  $B_E$

$$B = f(\theta) = \int_{t_1}^{t_E} e^{(\theta-r)} dt$$

using Eq. (3-18, 3-19)

$$\bar{B} = 18.3, \sigma_B = 6.7$$

- 2) Compute  $\overline{LCC}_E$

$$\overline{LCC} = \bar{C}_1 + \bar{C}_0 \bar{B}_0$$

$$= 5000 + (750)(18.3)$$

$$\overline{LCC}_E = 18,725$$

3) Compute the variance of LCC,  $\sigma^2_{LCC}$

using Eq. (3.28) (the same as mechanical system)

$$\begin{aligned}\sigma^2_{LCC_E} &= (500)^2 + (75)^2 (18.3)^2 + (6.7)^2 (750)^2 + \\ &\quad (6.7)^2 (75)^2 \\ &= (5257)^2\end{aligned}$$

The total life-cycle cost is equal to:

$$\begin{aligned}\overline{LCC} &= \overline{LCC_M} + \overline{LCC_E} \\ &= 77,625\end{aligned}$$

And  $\sigma_{LCC}$  is computed as follows:

a) If the correlation between the mechanical and electrical systems is assumed equal to zero, then:

$$\sigma^2_{LCC} = (28,118)^2 + (5257)^2$$

$$\sigma_{LCC} = \$28,605, \text{ c.v.} = .3685$$

b) If correlation exists between cost of different types of energy, and  $\rho = .9$ , we will have:

$$\begin{aligned}\sigma^2_{LCC} &= \sigma^2_{LCC} + \sigma^2_{LCC_E} + 2 \text{Cov} (LCC_M, LCC_E) \\ &= (28,605)^2 + 2((.9)(6.7)(25.57)(750)(1000))\end{aligned}$$

$$\sigma_{LCC} = \$32,396, \text{ c.v.} = .4173$$

The above example demonstrates the importance of incorporating the second moment (variance) in the LCC analysis. Special emphasis is on the time component of operating cost "B", which determines the risk allocations and controls its significance.

### 3.3 SELECTION OF ALTERNATIVES

Using the mean variance computed for life cycle cost of each element, there are many ways to select the best alternative; (i.e. there are different criteria by which alternatives can be ranked.) For example, capital cost, life-cycle cost, risk, etc. But rather than consider the above criterion independently, we can combine at least two of them into a single measure, i.e. LCC and risk.

In order to make the comparison procedure efficient, it is useful to first screen out the least desirable alternatives. The concept of efficiency frontier [13] may be employed for this screening task. It is based on the following principle. If there are two alternatives with equal expected life-cycle costs, the alternative which has a lower risk should be selected; if there are two alternatives with the same level of risk, the one with lower expected life-cycle cost should be selected (Fig. 3-4).

Once the screening of alternatives has been performed, the remaining ones must be ranked. Two methods are described here.

### 3.3.1 Use of Utility Theory

The basis for the utility theory has been well documented in many references [11, 14, 15]. According to the theory, each individual has a measurable preference among various choices available in a risk situation. This preference is called his utility. Utility is measured in arbitrary units which are called utiles. By suitable questioning, we can determine for each individual a relationship between utility and other measurable quantities (dollars), which is called a "utility function". This function offers a picture of his attitude towards taking risk.

In any decision involving risk, the decision maker will choose that alternative which maximizes his expected utility, which may be expressed as

$$M_{\max} U = \int U(x) f_x(x) dx$$

(3-32)

where  $x$  is the performance measure of interest which is a random variable with a density function  $f_x(x)$

a) For the polynomial case, where :

$$U = A_0 + A_1x + A_2x^2 + \dots \quad (3-33)$$

we may apply the expectation operator directly as follows :

$$\text{For } U = A_0 + A_1x \quad (3-34)$$

$$E(U) = A_0 + A_1\bar{x} \quad (3-35)$$

Thus, for this case maximizing expected utility is identical to maximizing the expected value.

$$\text{For } U = A_0 + A_1x + A_2x^2 \quad (3-36)$$

$$E(U) = A_0 + A_1\bar{x} + A_2(\sigma_x^2 + \bar{x}^2) \quad (3-37)$$

Here we need the mean and variance of the random variable  $x$ .

And for :

$$U = A_0 + A_1x + A_2x^2 + A_3x^3 \quad (3-38)$$

$$E(U) = A_0 + A_1\bar{x} + A_2(\sigma_x^2 + \bar{x}^2) + A_3(3\sigma_x^2\bar{x} + \bar{x}^3 + u_3(x)) \quad (3-39)$$

For this case, the additional information in the form of the skewness of the performance measure is required.

b) For the exponential utility case [16], we have :

$$U(x) = 1/s (1 - e^{-sx}). \quad (3-40)$$

In order to use this function, one must identify the coefficient  $s$ , which indicates the decision maker's attitude towards taking risks:

- i) if  $s > 0$ , then the decision maker is averse to risk, (Fig. 3-5).
- ii) if  $s = 0$ , then the decision maker is neutral towards risk, (Fig. 3-5);
- iii) if  $s < 0$ , then the decision maker exhibits a preference for risk, (Fig. 3-5);

The "Central Limit Theorem" (12) states that under very general conditions, as the number of variables in the sum becomes large, the distribution of the sum of random variables will approach the normal distribution. This theorem holds when we have independent variables and the distribution of variables are not identical. Since these conditions hold for Life-Cycle Cost Analysis, we can assume that the density function of LCC is "normal", (i.e. LCC can be fully described by its mean and variance), then the expected utility or risk adjusted value [16] of LCC is given by :

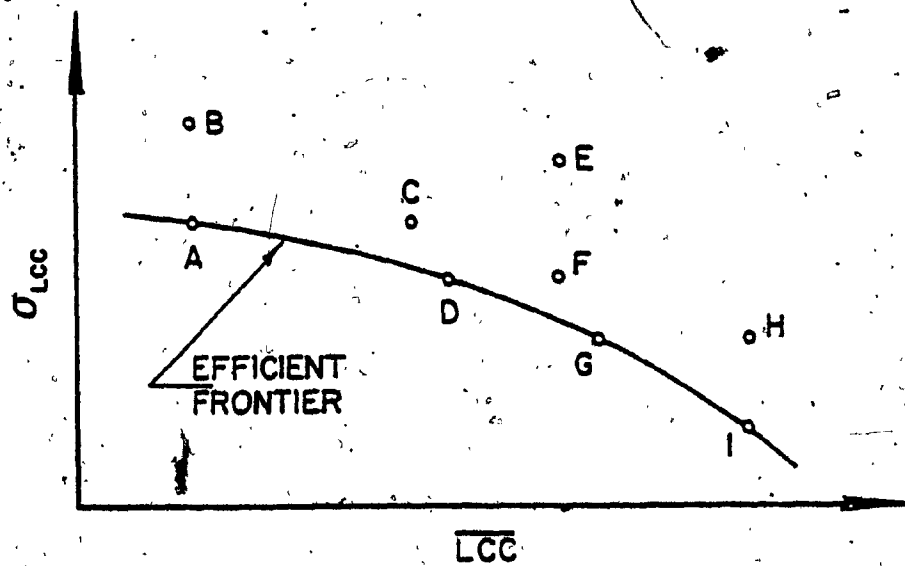


FIG. 3-4 - EFFICIENT FRONTIER FOR SCREENING ALTERNATIVES

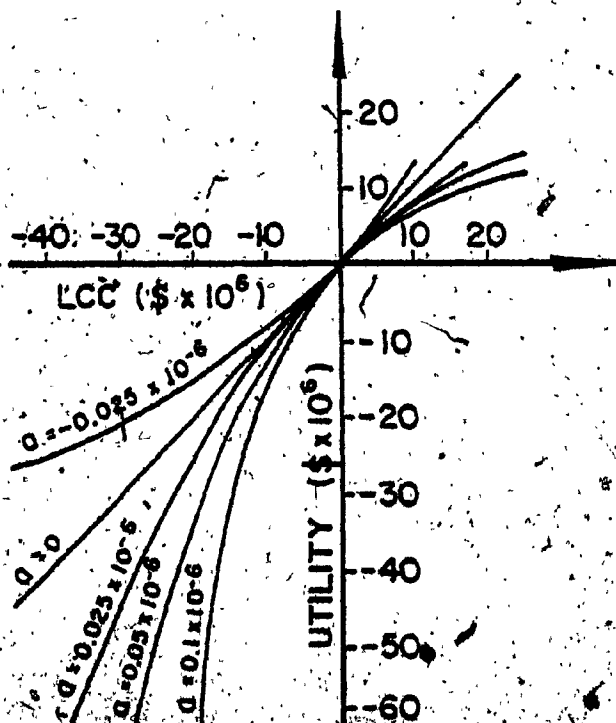


FIG. 3-5 - UTILITY CURVES FOR VARIOUS RISK ATTITUDES



$$\overline{U} = \overline{LCC} + 1/2 \cdot s \cdot \sigma^2 LCC$$

For a normal distribution and exponential utility, the risk adjusted value is the expected value of life-cycle cost, less a risk discount that is proportional to the variance of distribution and to risk aversion parameter "S". This function is also called the uncertainty equivalent of an investment. Thus, in the case of exponential utility, the following steps can be followed :

1. determine the coefficient of risk aversion, s;
2. using eqs. (3-27, 3-28), compute the mean and variance of life-cycle cost;
3. calculate the utility value from eq. (3-43).

### 3.3.2 Use of probability value

Assuming that the density function of life-cycle cost is normal, the alternatives could be ranked by minimizing the probability that LCC exceeds a specified life-cycle cost budget (see Fig. (3- )) :

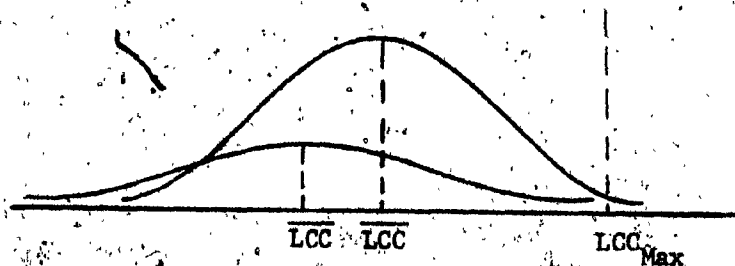


FIG. (3-6) - PROBABILISTIC DECISION RULE

The concept is to :

$$\text{Min } P[LCC < LCC_{\max}] \quad (3-41)$$

Since LCC is negative, we can say :

$$\text{Min } P[|LCC| > |LCC_{\max}|] \quad (3-42)$$

or

$$\text{Max } P[|LCC| < |LCC_{\max}|] \quad (3-43)$$

or

$$\text{Max } P\left[\frac{|LCC| - |\overline{LCC}|}{\sigma_{LCC}} < \frac{|LCC_{\max}| - |\overline{LCC}|}{\sigma_{LCC}}\right] \quad (3-44)$$

where :

$$\frac{|LCC| - |\overline{LCC}|}{\sigma_{LCC}} = z, \quad \frac{|LCC_{\max}| - |\overline{LCC}|}{\sigma_{LCC}} = z$$

Therefore, we want to :

$$\text{Max } P[Z < z]$$

(3-48)

Then, the procedure for ranking alternatives is as follows :

1. Compute the mean and variance of LCC for each alternative;  $(\bar{LCC}, \sigma^2_{LCC})$ ;
2. determine the budget cost;  $(LCC_{\max})$
3. compute Z using :

$$z_1 = \frac{LCC_{\max} - LCC_1}{\sigma_{LCC_1}}$$

(3-49)

4. choose the alternative corresponding to minimum value of  $z_1$ .

For example :

$$LCC_1 = 10,000, \sigma_{LCC_1} = 2000$$

$$LCC_2 = 10,500, \sigma_{LCC_2} = 1000 \text{ and } LCC_{\max} = 11,000$$

$$z_1 = \frac{11,000 - 10,000}{2,000} = .5, \quad z_2 = \frac{11,000 - 10,500}{1,500} = .33$$

Choose first alternative as a better alternative.

A variation of the above procedure is to rank alternatives according to a fixed level of risk. This method can be described as :

1. find the corresponding value of  $z$  using normal tables [11]. For example, if  $p = 15\%$ ,  $z = 1.036$ ;
2. using eq. (3-49), and mean and variance of LCC, compute the value of LCC;
3. choose the alternative that yields the minimum value of LCC;

For example :

Using the previous examples, data for  $p = 15\%$ ,  $z = 1.036$  :

$$LCC_{\max_1} = (1.036)(2000) + 10,000 = 12,072$$

$$LCC_{\max_2} = (1.036)(2500) + 10,500 = 12,044$$

select the second alternative as the best.

Measuring risk and incorporating with life-cycle cost have been presented in different ways. By using polynomial utility function, it is assumed that the attitude of decision maker continuously varies with variation in investment level. Difficulties in determination of this variation makes it very difficult to use in design offices in which decision-making is a daily practice.

Using first and second moments (mean and variance) only, the exponential utility function introduces a constant risk factor. The assumption eases the use of this function for risk evaluation. In order to define the decision-maker behaviour in a more exact manner, one might use a set of exponential utility functions with different risk factors, e.g.:

20 M\$ (LCC  $\leq$  40M\$)

$$s = +.025 (10^{-6})$$

10 M\$ (LCC  $\leq$  20M\$)

$$s = +.05 (10^{-6})$$

LCC  $\leq$  10M\$

$$s = +.1 (10^{-6})$$

One of the most appropriate definitions for risk is "the probability of failure", which in investment problems is "the probability of exceeding a ceiling budget". The probability value concept is based on this definition, and it is the most useful concept at present for use by decision-makers in construction industry.

## CHAPTER 4

The purpose of this chapter is to discuss a computerized decision aid which incorporates the concepts and relationships discussed in Chapters 2 and 3.

### 4.1 PROGRAM OBJECTIVES

The immediate objectives adopted for developing an interactive computer-based life-cycle cost decision aid are as follows :

1. To be able to analyze the project at two levels. Level I deals with building subsystems (e.g. enclosure, structure, etc.) and Level II treats the building elements for each subsystem (e.g. considering enclosure, they could be walls, windows, doors and roof);
2. To calculate capital cost, life-cycle cost and risk at each level, for use in ranking the alternatives;
3. To be able to choose the most desirable alternative for each element of a building subsystem (level II);
4. To be able to edit the data in order to conduct sensitivity analyses; and
5. To make the program as flexible as possible in order to allow future additions as described in Chapter 1.

The long-term goals beyond this thesis for program development deal with incorporating design and optimization routines as follows.

1. To incorporate preliminary analysis and design routines which can be used to generate input necessary for a level II analysis (e.g. computer package developed by Choudhary [1]);
2. To incorporate optimization techniques for both single-attributed and multi-attributed decision making, both for deterministic and probabilistic formulations as described in Chapter 1. These techniques shall be used to optimize building subsystem performance by determining optimum values for the variables describing each subsystem, as well as for the co-ordination variables which link the various building subsystems;
3. To create a storage file to allow for multiple sessions with the same problem data; and
4. To add to a data base giving cost rates, regression models, etc., for modeling of time variations.

#### 4.2 INPUT OF COST DATA

Capital costs can be treated as deterministic or probabilistic. For the probabilistic case, input consists of the expected value and coefficient of variation for each capital cost item.

Life-cycle cost data consists of :

- a) Base year cost and its coefficient of variation;
- b) Time model type;
- c) Time model parameters (coefficients for time model);

- d) Utility function parameters;
- e) Study period, MARR, and tax rate.

#### 4.3 SENSITIVITY ANALYSIS

Prior to making a final investment decision, it is worthwhile to evaluate the sensitivity of economic performance to changes in the values of key parameters about which there is uncertainty, e.g. energy cost and enclosure cost. This can be done by recomputing the life-cycle cost measure for different values of the parameters in question, using a technique called sensitivity analysis. The results of a sensitivity analysis enable the decision maker to consider the consequences associated with alternative parametric values. By examining the results, the decision maker is better able to decide if an investment should be undertaken. In this program, the user selects the data which he wishes to change, inputs the information and executes the program. A very important section of this program which is called "RERUN" is designed for this purpose.

#### 4.4 PROGRAM DESCRIPTION

The program is called "LIFE" and is designed to be used in an interactive mode. An attempt has been made to have it suitable for direct use in engineering and architectural design offices. The program consists of three main parts (Fig. (4-1)) :

- a) Input interface : This section deals with the initial inputs and any revisions required for sensitivity anal-



1 - INPUT INTERFACE

2 - OPERATIONAL INTERFACE

3 - OUTPUT INTERFACE

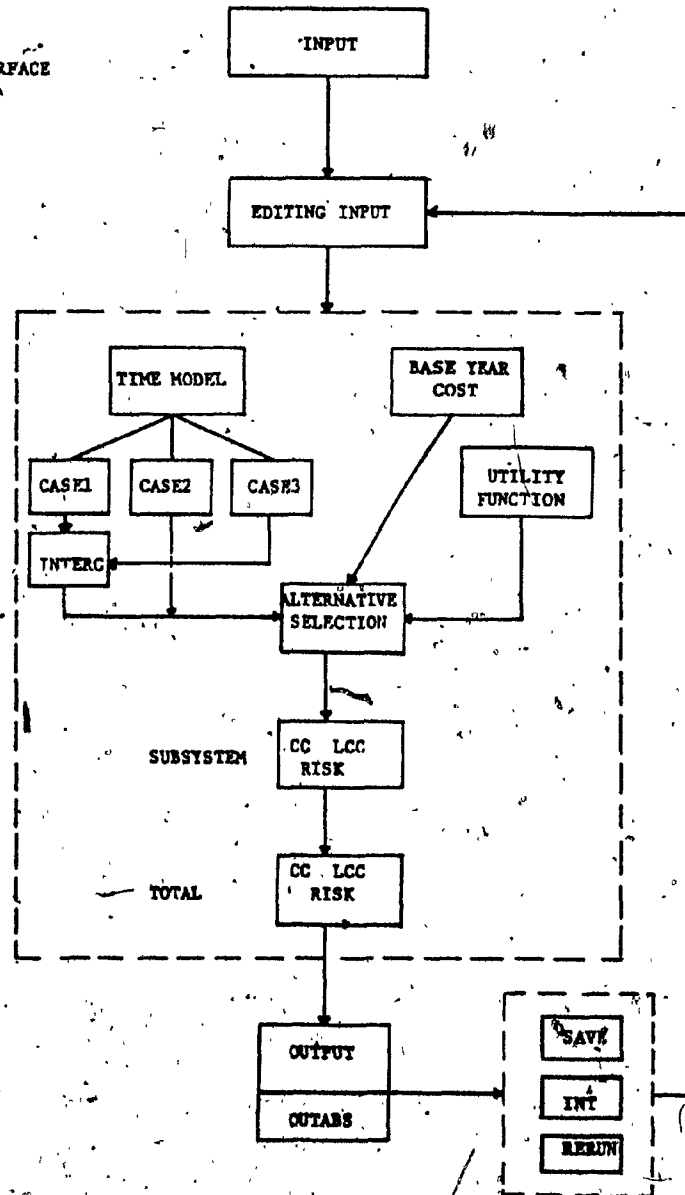


FIG. 4-1 - GENERAL STRUCTURE OF PROGRAM "LIFE"

ysis. At present, the tax rate, period of study, utility function parameters and MARR cannot be revised.

- b) Operational interface : In this section, capital cost, life-cycle cost and risk are computed. Detailed information about time models is also output.
- c) Output interface : In this section, tabulated information (capital cost, life-cycle cost, risk and utility values) is made available to the user for decision making purposes.

Specifically, the program consists of one main program and eight sub-routines.

1. Main Program

The functions of the main program include :

- a) structuring of the problem at hand, using the Uniformat Structure. The standard format Table (2-1), forms an integral part of the main program. The user may increase the number of elements, alternatives and subsystems as required for the problem at hand. New elements or subsystems can be created in the memory after standard elements and/or subsystems are finished, e.g. the new element "chiller" is added and is shown on page 140; and
- b) computation of total life-cycle cost based on detailed information fed from various sub-routines.

2. Sub-Routine "OUTABS"

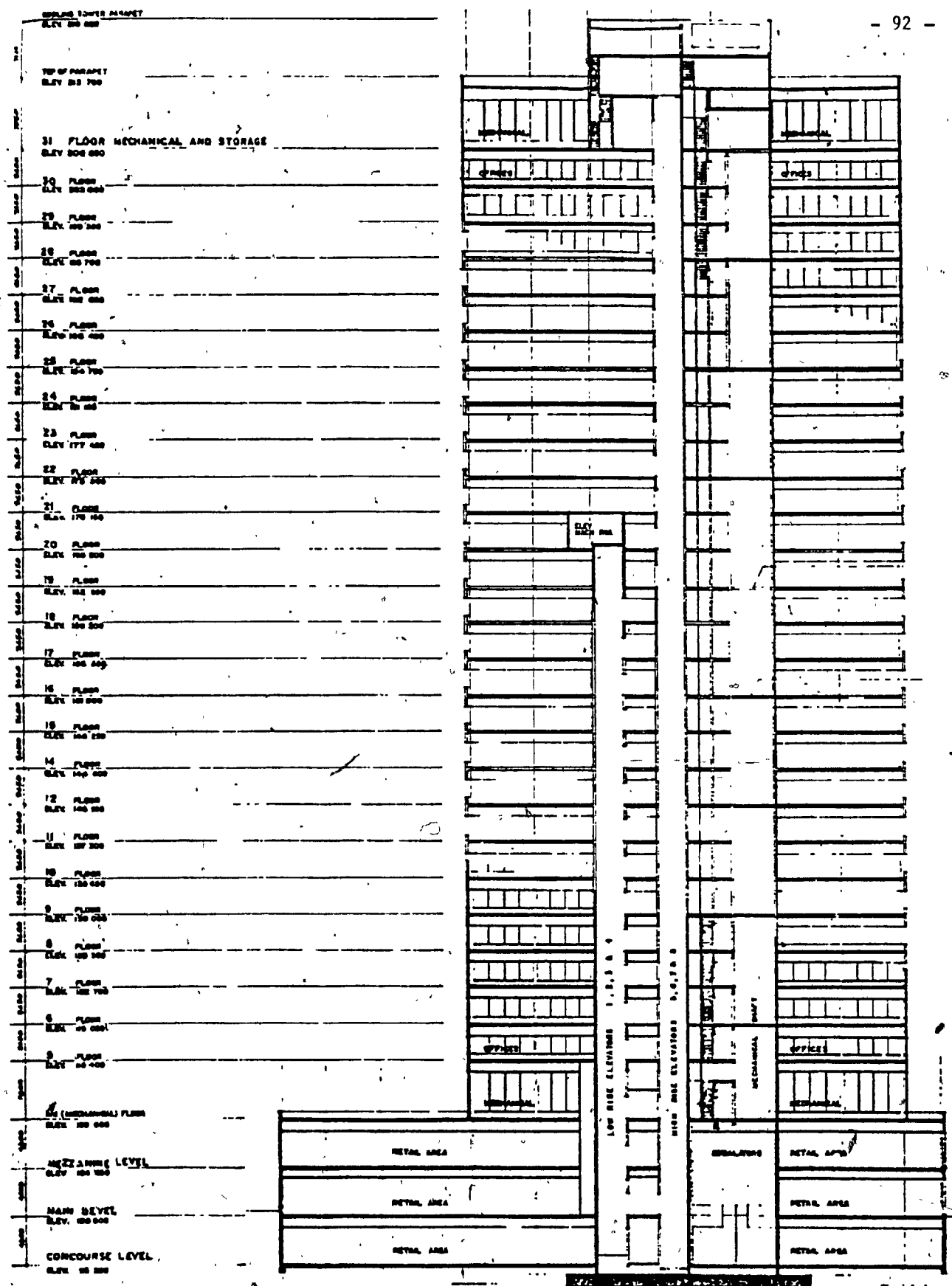
This sub-routine is constructed for the purpose of outputs. Two types of output are designed :

|   | Gross<br>ft <sup>2</sup> | Rentable<br>ft <sup>2</sup> |
|---|--------------------------|-----------------------------|
| <b>LAND AREA</b>                          |                          |                             |
| OFFICE SITE                               | 32,000                   | ---                         |
| PARKING SITE                              | <u>19,100</u>            | ---                         |
|   | 51,100                   |                             |
| <b>BUILDING AREA</b>                      |                          |                             |
| <u><b>A. RETAIL</b></u>                   |                          |                             |
| Concourse Level                           | 31,375                   | 21,782                      |
| Street Level                              | 28,423                   | 21,935                      |
| Mezzanine Level                           | 25,663                   | 21,750                      |
| Ground Floor Parkade & Underground Pedway | <u>15,900</u>            | <u>7,500</u>                |
| <b>TOTAL RETAIL</b>                       | 101,361                  | 72,967                      |
| <b>* <u>B. OFFICE</u></b>                 |                          |                             |
| 2 Part Floors (3 & 4)                     | 28,948                   | 14,474                      |
| 11 Typical Low Rise (5-15)                | 159,214                  | 144,364                     |
| 14 Typical High Rise (16-30)              | 202,638                  | 188,636                     |
| 2 Mechanical & Elevators Rooms (2 & 31)   | <u>14,474</u>            | <u>---</u>                  |
| <b>TOTAL OFFICE</b>                       | 405,272                  | 347,474                     |
| <b>RETAIL &amp; OFFICE AREA TOTALS</b>    | 506,633                  | 420,441                     |
| <u><b>C. PARKING</b></u>                  |                          |                             |
| Floor Area (6 storeys)                    | 126,200                  |                             |
| <b>BUILDING AREA TOTALS</b>               | <u><u>632,833</u></u>    | <u><u>420,441</u></u>       |

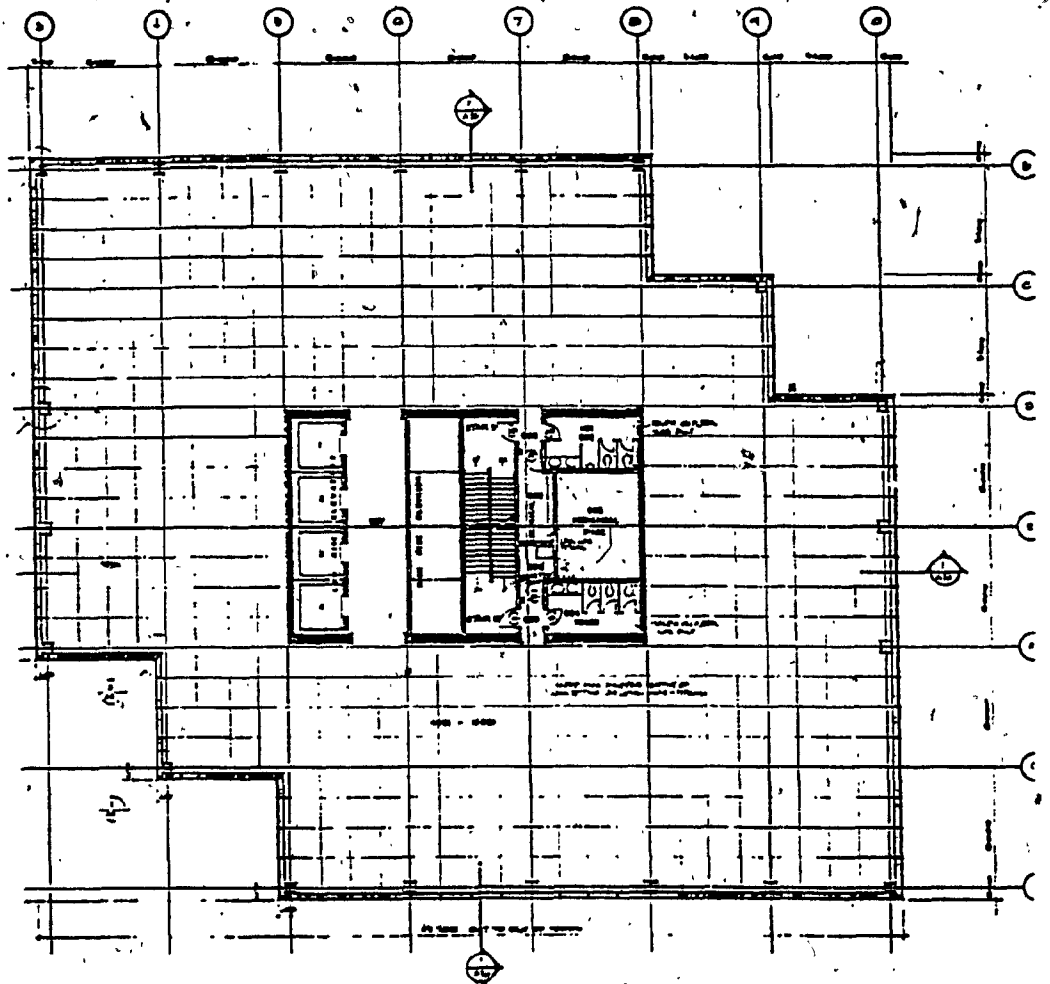
\* NOTE: No 13th Floor

AREA SUMMARY

TABLE 5-1 [16]



BUILDING ELEVATIONS  
FIG. 5-1 [16]



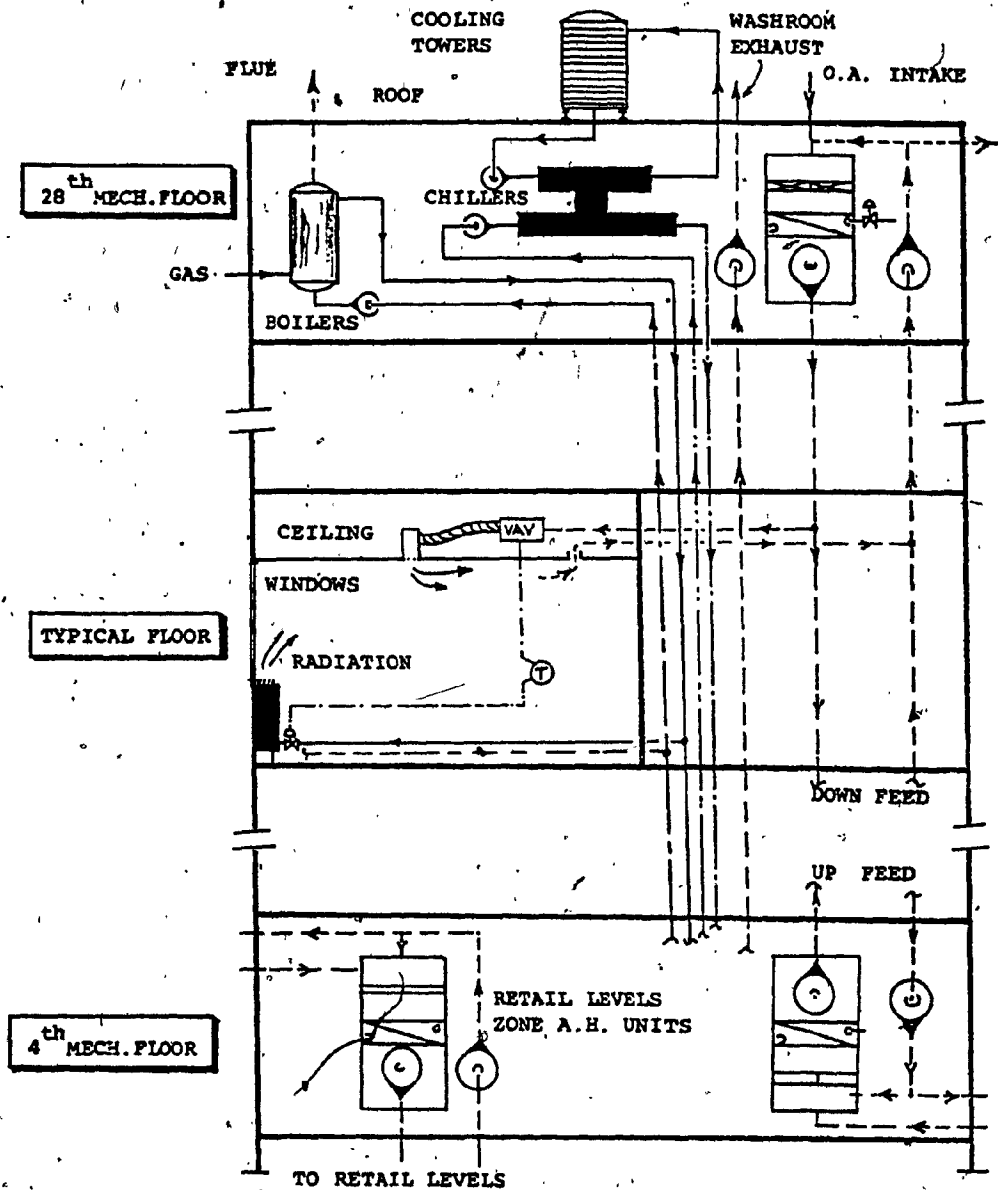
TYPICAL BUILDING FLOOR PLAN

FIG. 5-2 [16]

The building is served by eight high-speed gearless elevators in two banks. Four serve low rise floors, one through fifteen inclusive, at a speed of 500 feet per minute. Four serve the high-rise floors, sixteen through twenty-nine, with service from the first and second retail levels, at speeds of 700 feet per minute.

The building has sprinkler protection throughout and smoke detectors at every floor with smoke exhaust and stairwell pressurization systems as per local building codes. Security systems allow for programmed elevators during after hours and 24 hour building watch tour security.

The mechanical systems were designed to accommodate maximum tenant fit-up flexibility of partitions while maintaining efficient control and energy use. A Variable Air Volume (VAV) air distribution system was chosen which permitted minimum office core sizes. High-pressure "express" air duct risers from a central fan system serves the VAV boxes on each floor. Perimeter office floor heating was designed for hot water radiation at the window locations. Sequential heating and cooling control of radiation and VAV boxes by means of pneumatic thermostats was designed for the perimeter areas. Two (2) central system mechanical rooms, complete with chillers, boilers, pumps and fans, are installed on the top floor and fourth floor and allow for up and down feed of air and water for heating, ventilation and air conditioning (HVAC). A schematic of the HVAC system is shown in Fig. (5.3) [16].



HVAC SYSTEM SCHEMATIC

FIG. 5-3 [16]

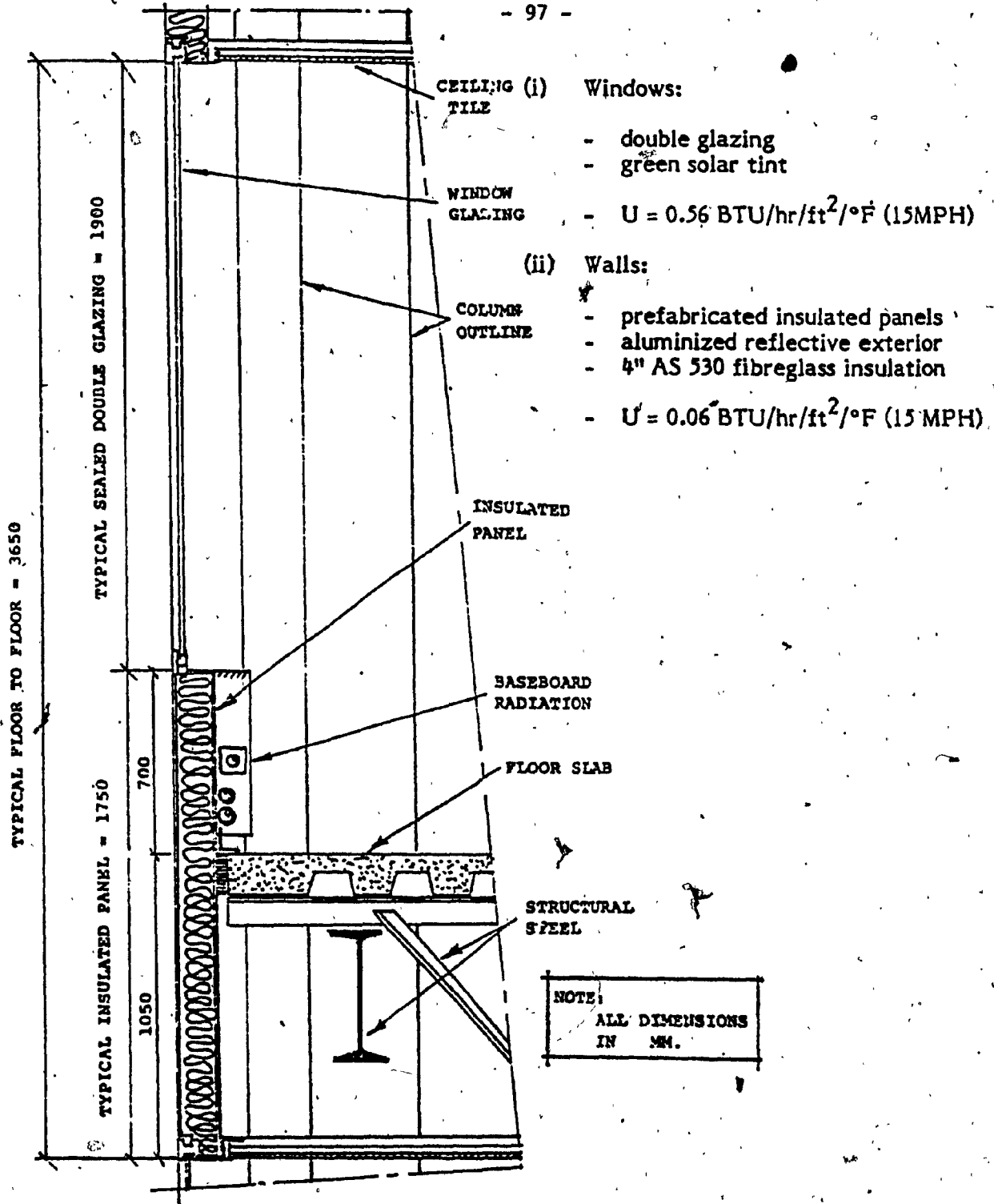
The building wall systems consist of 4" insulated aluminum panels with green tinted double glazing window sections. Glass area and wall panel area for the typical wall module constitute approximately 52% and 48% respectively of the total building perimeter area. Neutral tone sun drapes are provided on all windows. Details of a typical wall section are shown in Fig. (5.4) [16].

A common five foot by five foot ceiling module, with recessed fluorescent light fixtures sufficient to maintain an illumination of 75 foot-candles at desk level, is thought possible with a "checker-board" light fixture layout. This amounts to an average 2.3 w/ft<sup>2</sup> energy consumption for lighting, including standard ballasts. Light switching for each floor, with tenant switching override, forms part of the design. Special light fixtures with aluminized parabolic reflector design and "warm" light fluorescent tubes are used to obtain maximum lighting efficiency and minimum energy consumption. The added cost for this change was \$200,000, but electricity usage dropped from 3 watts/sq.ft. to 2.3 watts/sq.ft. The illumination system treated in the analysis herein reflects the 3 w/ft<sup>2</sup> system.

## 5.2 ENERGY ANALYSIS

To date, eleven enclosure treatments have been studied to determine their impact on energy consumption, capital cost, life-cycle cost and risk. Variations in glazing type and insulation thickness have been considered. Energy analyses were conducted using the Meriwether Systems Analysis Program [47]. Climatic conditions for Edmonton, Al-





BUILDING PERIMETER SECTION

FIG. 5-4 [16]

berta, form the basis for the energy analyses. Energy consumption data for the enclosure strategies examined are presented in Table 5.2. The mechanical system was not resized for any of the alternatives studied. The unit costs of the wall system given in Table 5.2 were obtained directly from the supplier. The spread in these costs is quite low, with the difference in total cost between the least expensive and most expensive alternative being \$471,697. Note that alternative 5 corresponds to the design selected. The variation in energy consumption between the alternatives considered is not large. It is of interest to note how much of the energy consumed is in the form of lights and power (3.15 watts/ft<sup>2</sup>). Thus, money might be more advantageously spent on the illumination system than on the enclosure system to reduce energy consumption. This was in fact done, as described previously.

The following values were utilized for computing LCC,  $\sigma^2_{LCC}$  and expected utility of LCC. The capital costs of the enclosure, mechanical and electrical systems equal the unit rates in Table 2, times the gross wall area, \$2,380,810 and \$1,626,900, respectively. A coefficient of variation of 0.025 was assumed for all capital cost items, except for the enclosure alternatives which have 6 inches of insulation. For this case, the coefficient of variation for enclosure capital cost was set at 0.05. The reason for this was that the supplier consulted had not fabricated a panel with 6 inches of insulation to date, and he was not sure of his price for this case. Existing energy rates of \$1.143/MCF for gas and \$0.0242/kwatt for electricity were taken as

| GLAZING<br>TREATMENT      | WALL PANEL<br>INSULATION<br>ENCLOSURE &<br>ENERGY DESCRIPTIONS | PANEL INSULATION<br>THICKNESS |            |            |
|---------------------------|--|-------------------------------|------------|------------|
|                           |  | 2"                            | 4"         | 6"         |
| Clear<br>Double           | U Glass  | 0.490                         | 0.490      | 0.490      |
|                           | U Panel  | 0.114                         | 0.060      | 0.040      |
|                           | <sup>1</sup> U Effective                                       | 0.310                         | 0.284      | 0.274      |
|                           | SC   | 0.88                          | 0.88       | 0.88       |
|                           | <sup>2</sup> Wall Cost \$/ft <sup>2</sup>                      | 18.35                         | 18.60      | 18.85      |
|                           | <sup>3</sup> Heating MBH/yr                                    | 19,130,252                    | 17,683,351 | 17,142,923 |
|                           | Chiller KWH/yr   | 316,666                       | 317,444    | 317,883    |
|                           | <sup>4</sup> Lights & Power KWH/yr                             | 6,078,194                     | 6,082,449  | 6,082,764  |
|                           | <sup>5</sup> Total Energy KWH/ft <sup>2</sup> /yr              | 37.17                         | 35.87      | 35.38      |
| Tint<br>Double            | U Glass  | 0.430                         | 0.430      | 0.430      |
|                           | U Panel  | 0.114                         | 0.060      | 0.040      |
|                           | U Effective  | 0.278                         | 0.252      | 0.243      |
|                           | SC   | 0.58                          | 0.58       | 0.58       |
|                           | Wall Cost \$/ft <sup>2</sup>                                   | 19.75                         | 20.00      | 20.25      |
|                           | Heating MBH/yr   | 17,425,917                    | 15,965,057 | 15,402,236 |
|                           | Chiller KWH/yr   | 295,786                       | 296,157    | 298,186    |
|                           | Lights & Power KWH/yr  | 6,000,211                     | 5,980,829  | 5,998,737  |
|                           | Total Energy KWH/ft <sup>2</sup> /yr                           | 35.33                         | 33.94      | 33.48      |
| Reflec-<br>tive<br>Double | U Glass  |                               | 0.430      | 0.430      |
|                           | U Panel  |                               | 0.060      | 0.040      |
|                           | U Effective  |                               | 0.252      | 0.243      |
|                           | SC   |                               | 0.38       | 0.38       |
|                           | Wall Cost \$/ft <sup>2</sup>                                   |                               | 21.00      | 21.25      |
|                           | Heating MBH/yr   | NOT<br>RUN                    | 15,950,085 | 15,409,892 |
|                           | Chiller KWH/yr   |                               | 256,798    | 257,705    |
|                           | Lights & Power KWH/yr  |                               | 5,838,550  | 5,841,845  |
|                           | Total Energy KWH/ft <sup>2</sup> /hr                           |                               | 33.87      | 32.89      |
| Clear<br>Triple           | U Glass  | 0.310                         | 0.310      | 0.310      |
|                           | U Panel  | 0.114                         | 0.060      | 0.040      |
|                           | U Effective  | 0.216                         | 0.190      | 0.180      |
|                           | SC   | 0.71                          | 0.71       | 0.71       |
|                           | Wall Cost \$/ft <sup>2</sup>                                   | 20.75                         | 21.00      | 21.25      |
|                           | Heating MBH/yr   | 13,903,700                    | 12,458,151 | 11,917,873 |
|                           | Chiller KWH/yr   | 312,513                       | 313,368    | 313,712    |
|                           | Lights & Power KWH/yr  | 6,057,884                     | 6,062,181  | 6,064,173  |
|                           | Total Energy KWH/ft <sup>2</sup> /yr                           | 32.36                         | 31.06      | 30.58      |

<sup>1</sup> U Effective = 0.52 \*Glass + 0.48 \*U Panel

<sup>2</sup> Gross Wall Area = 162,654 ft<sup>2</sup>

<sup>3</sup> Overall Boiler, Pumping and Piping Efficiency = 75%

<sup>4</sup> Light & Auxiliary Power Use 3.15 Watts/ft<sup>2</sup>

<sup>5</sup> Net Leasable space = 322,787 ft<sup>2</sup>

Note : 1 KWH = 3412 BTU

TABLE 5-2 DATA FOR ENERGY CONSERVATION STRATEGIES

| TIME VARIATION MODEL FOR GAS           |      |                    | TIME VARIATION MODEL FOR ELECTRICITY    |      |                   |
|--|------|--------------------|---|------|-------------------|
| INFLATION MODELS                       | P    | B                  | INFLATION MODELS                        | P    | B                 |
| 1. $\theta = .25$                      | .025 |                    | 1. $\theta = .20$                       | .025 |                   |
| 2. $\theta = .25 + .0025t$             | .025 | $t_1 = 1.5$ yrs    | 2. $\theta = .2 + .0025t$               | .025 | $t_1 = 1.5$ yrs   |
| 3. $\theta = .25 + (.25 - .10)e^{-dt}$ |      | $T_E = 20$ yrs     | 3. $\theta = .075 + (.2 - .075)e^{-dt}$ |      | $T_E = 20$ yrs    |
| a) $\theta = 10.5\%$ after 10 yr       | .2   | B=8                | a) $\theta = 8\%$ in 10 yrs             | .2   | B=5               |
| b) $\theta = 10.5\%$ after 20 yr       | .4   | $\sigma_B = 18.99$ | b) $\theta = 8\%$ in 20 yrs             | .4   | $\sigma_B = 9.19$ |
| c) $\theta = 10.5\%$ after 30 yr       | .2   |                    | c) $\theta = 8\%$ in 30 yrs             | .2   |                   |
| d) $\theta = 10.5\%$ after 40 yr       | .15  |                    | d) $\theta = 8\%$ in 40 yrs             | .15  |                   |

TABLE 5.3

TIME VARIATION SCENARIOS

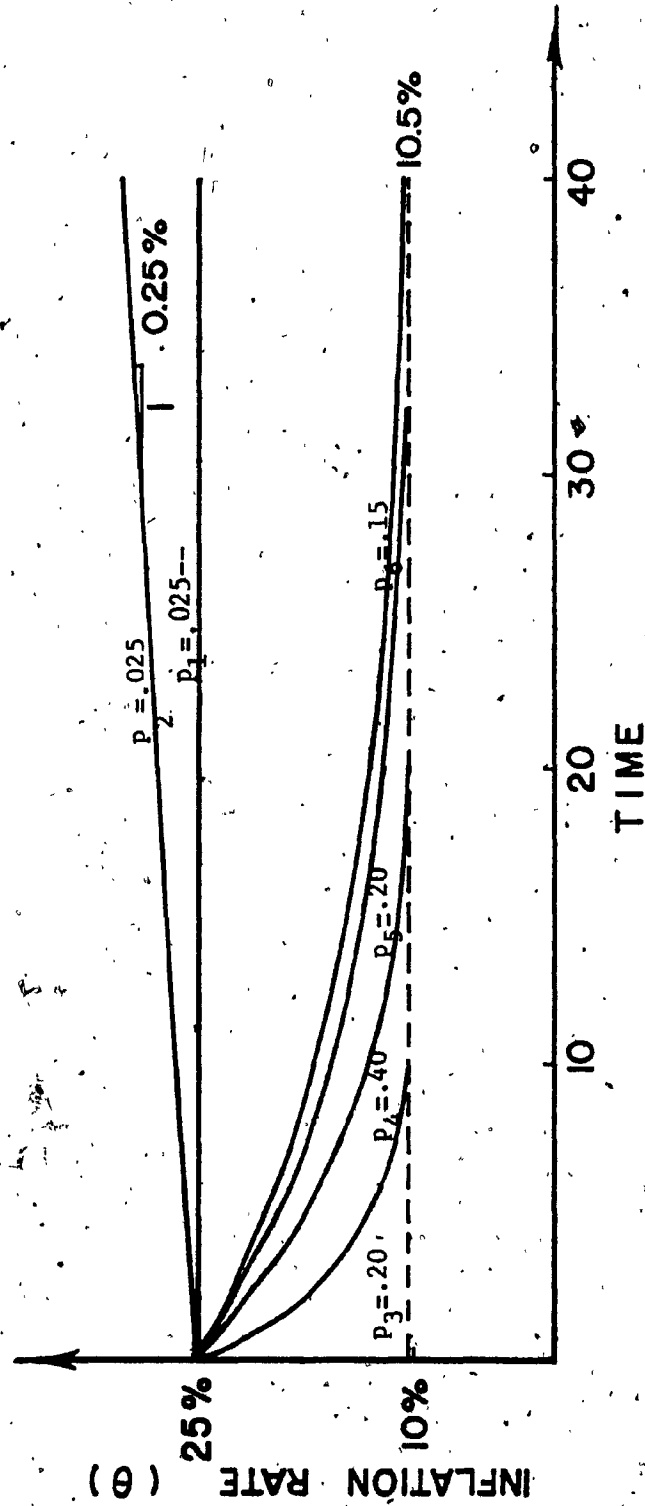


FIG. 5-5 - INFLATION SCENARIOS USED IN CASE STUDIES

time zero costs. The heating system is gas fired, while electricity is used for cooling and lights and power. The cost for electrical power does not include demand charges. The mean and variance of energy cost time models were computed using equations (3-18, 3-19). Time variation scenarios for gas and electricity were selected, as shown in Table 5.3 and Fig. 5.5

For electricity, time models similar to those used for gas were selected to reflect the fact that electricity in Alberta is generated by burning both gas and coal. No maintenance, repair or alteration costs were included for any subsystem. A study period of 20 years, tax rate of zero and discount rate of 15 percent were selected for illustrative purposes. It should be noted that risk is maximized for the case of  $T = 0$ .

Computer runs were made for 1, 2 and 4 times base year energy costs to reflect existing costs at different geographic locations. Construction period and study period are 1.5 and 21.5 years, respectively. Table 5.4 contains cost and risk data describing each alternative. The data show that most of the risk comes from the future costs and that capital cost forms a very substantial percentage of life cycle cost for the project examined. For a given base year energy cost multiplier, as presented in Tables 5.4 and 5.5, the spread in both  $LCC$  and  $\sigma LCC$  is not large mainly because the differences in energy consumption between alternatives are small and because the mechanical system was not resized to take account of reduced heating and cooling loads. Nevertheless, the risk assumed by the investor, as

|    | Capital Cost | $\sigma$ Capital Cost | LIFE CYCLE COST DATA              |                |           |                |            |                |     |                |
|----|--------------|-----------------------|-----------------------------------|----------------|-----------|----------------|------------|----------------|-----|----------------|
|    |              |                       | BASE YEAR ENERGY PRICE MULTIPLIER |                |           |                |            |                |     |                |
|    |              |                       | 1X                                |                | 2X        |                | 4X         |                |     |                |
|    |              |                       | LCC                               | $\sigma_{LCC}$ | LCC       | $\sigma_{LCC}$ | LCC        | $\sigma_{LCC}$ | LCC | $\sigma_{LCC}$ |
| 1  | 6,992,409    | 104,886               | 7,888,628                         | 1,427,842      | 8,784,848 | 2,855,076      | 10,577,287 | 5,701,158      |     |                |
| 2  | 7,033,072    | 105,496               | 7,954,768                         | 1,407,994      | 8,876,465 | 2,831,592      | 10,719,857 | 5,649,365      |     |                |
| 3  | 7,073,736    | 169,770               | 7,953,168                         | 1,423,617      | 8,832,601 | 2,835,265      | 10,591,466 | 5,655,843      |     |                |
| 4  | 7,220,125    | 108,302               | 8,090,124                         | 1,399,591      | 8,960,122 | 2,795,558      | 10,700,119 | 5,596,162      |     |                |
| 5  | 7,260,788    | 108,912               | 8,152,680                         | 1,385,956      | 9,044,572 | 2,740,505      | 10,828,355 | 5,522,461      |     |                |
| 6  | 7,301,452    | 182,536               | 8,153,793                         | 1,394,299      | 9,006,135 | 2,773,890      | 10,710,817 | 5,548,203      |     |                |
| 7  |              |                       | NOT RUN                           |                |           |                |            |                |     |                |
| 8  | 7,423,442    | 111,352               | 8,257,650                         | 1,362,512      | 9,091,857 | 2,709,373      | 10,760,272 | 5,412,417      |     |                |
| 9  | 7,464,106    | 186,603               | 8,294,029                         | 1,368,515      | 9,123,952 | 2,709,814      | 10,783,798 | 5,413,467      |     |                |
| 10 | 7,382,778    | 110,742               | 8,230,332                         | 1,399,156      | 9,077,886 | 2,786,911      | 10,772,993 | 5,569,637      |     |                |
| 11 | 7,423,442    | 111,352               | 8,258,889                         | 1,387,493      | 9,094,335 | 2,773,772      | 10,765,229 | 5,544,093      |     |                |
| 12 | 7,464,106    | 186,603               | 8,295,073                         | 1,393,572      | 9,126,041 | 2,774,316      | 10,787,976 | 5,545,020      |     |                |

TABLE 5-4 - CAPITAL COST, LIFE CYCLE COST AND RISK FOR DESIGN ALTERNATIVES

(NO CORRELATION)

|    | Capital Cost | Capital Cost | LIFE CYCLE COST DATA              |              |            |                  |            |                  |                  |                  |
|----|--------------|--------------|-----------------------------------|--------------|------------|------------------|------------|------------------|------------------|------------------|
|    |              |              | BASE YEAR ENERGY PRICE MULTIPLIER |              |            |                  |            |                  |                  |                  |
|    |              |              | 1X                                |              | 2X         |                  | 4X         |                  | σ <sub>LCC</sub> | σ <sub>LCC</sub> |
|    |              |              | <u>LCC</u>                        | % <u>LCC</u> | <u>LCC</u> | σ <sub>LCC</sub> | <u>LCC</u> | σ <sub>LCC</sub> |                  |                  |
| 1  | 6,992,409    | 104,886      | 7,888,628                         | 1,814,403    | 8,784,848  | 3,628,328        | 10,577,287 | 7,249,583        |                  |                  |
| 2  | 7,033,072    | 105,496      | 7,954,768                         | 1,776,737    | 8,876,465  | 3,565,393        | 10,719,857 | 7,120,739        |                  |                  |
| 3  | 7,073,736    | 169,770      | 7,953,168                         | 1,780,825    | 8,832,601  | 3,552,090        | 10,591,466 | 7,092,462        |                  |                  |
| 4  | 7,220,125    | 108,302      | 8,090,124                         | 1,757,182    | 8,960,122  | 3,511,479        | 10,700,119 | 7,026,975        |                  |                  |
| 5  | 7,260,788    | 108,912      | 8,152,660                         | 1,722,452    | 9,044,572  | 3,419,685        | 10,828,355 | 6,872,632        |                  |                  |
| 6  | 7,301,452    | 182,536      | 8,153,793                         | 1,721,554    | 9,006,135  | 3,431,205        | 10,710,817 | 6,862,754        |                  |                  |
| 7  |              |              |                                   |              | NO RUN     |                  |            |                  |                  |                  |
| 8  | 7,423,442    | 111,352      | 8,257,650                         | 1,688,071    | 9,091,857  | 3,363,522        | 10,760,272 | 6,721,948        |                  |                  |
| 9  | 7,464,106    | 186,603      | 8,294,029                         | 1,684,765    | 9,123,952  | 3,347,461        | 10,783,798 | 6,689,935        |                  |                  |
| 10 | 7,382,778    | 110,742      | 8,230,332                         | 1,707,201    | 9,077,886  | 3,405,064        | 10,772,993 | 6,806,699        |                  |                  |
| 11 | 7,423,442    | 111,352      | 8,258,889                         | 1,674,280    | 9,094,335  | 3,347,554        | 10,765,229 | 6,692,249        |                  |                  |
| 12 | 7,464,106    | 186,603      | 8,295,073                         | 1,670,583    | 9,126,041  | 3,330,382        | 10,787,976 | 6,657,755        |                  |                  |

TABLE 5-5 - CAPITAL COST, LIFE CYCLE COST AND RISK FOR DESIGN ALTERNATIVES  
( WITH CORRELATION )



measured by  $\sigma_{LCC}$  can be substantial. Further, it is possible to exert at least partial control over this risk by effective design of the energy system.

Computed  $\sigma_{LCC}$  can be used for different purposes :

- 1) ranking of alternatives;
- 2) identifying the uncertainty sources which have to be controlled. The contribution of each component in the LCC equation to variance can be identified. Attention can then be directed at allocating risks which cannot be further reduced, redesigning or refining designs to reduce other risks and seeking more information to refine the estimate of risk (e.g. time models, etc.).

For the case in which correlations are ignored, rankings of the energy conservation strategies are presented in Tables 5.6. Criteria used for the rankings include capital cost, expected utility for risk prone, risk neutral and risk averse behaviour, minimum probability of exceeding a minimum fixed life cycle cost budget of  $\$12 \times 10^6$  (for base year cost multiplier of 1),  $\$13.5 \times 10^6$  (for base year cost multiplier of two),  $\$16 \times 10^6$  (for base year cost multiplier of four), and minimum life cycle cost for a given risk level equal to 15 per cent.

Alternative 1, which has the lowest capital cost, and highest standard deviation for life cycle cost is the best solution in all cases except when the base year energy price multiplier is 4 and the decision maker is exceedingly risk averse ( $s = 0.1 \times 10^{-6}$ ) or the last

criterion identified in Table 5.4 is employed. The rankings do change, however; as one goes from a base year energy cost multiplier of one to four and from risk-prone to risk-averse behaviour.

An analysis was also conducted based on the assumption that correlation exists between costs of different types of energy (e.g. between costs of gas and electricity, the coefficient of correlation  $\rho$  is set equal to .9) and  $\rho = 1$  for systems which use the same energy source). Using eq. (3.7),  $\sigma$  is calculated (by considering the correlation between the cost of different systems, the value of  $\sigma$  increases substantially), and the ranking of alternatives are presented in Table 5.7 (a computer program was written for the correlation computation). Alternative 1 is the best solution in all the cases except when the base year cost is a multiplier of 4. But ranking changes as one moves from risk-prone case to risk-averse behaviour. Comparing Tables 5.6 and 5.7, it is clear that the influence of correlation should not be neglected.

The efficient frontiers in the case of no correlation are constructed for screening of alternatives for energy cost multipliers one, two and four, as described in Chapter 3 are depicted in Figures 5.6, 5.7 and 5.8. This preliminary screening allows the number of alternatives to be reduced substantially, e.g. in Fig. (5.6), alternatives 6, 10, 11, 12 can be eliminated by the screening process.

| Rank | RANKING CRITERION* |                         |                        |                       |                       |                      |                      |                      |                      |                      |                      |                      |                      |                      |                      |                      | P[LCC < BUDGETED]<br>= min. |    |    |    | P[LCC < 1c <sub>q</sub> ]<br>= 0.15 |  |  |  |
|------|--------------------|-------------------------|------------------------|-----------------------|-----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|-----------------------------|----|----|----|-------------------------------------|--|--|--|
|      | Capital Cost       | EXPECTED UTILITY        |                        |                       |                       |                      |                      |                      |                      |                      |                      |                      |                      |                      |                      |                      |                             |    |    |    |                                     |  |  |  |
|      |                    | z = 0                   |                        |                       |                       |                      |                      |                      |                      |                      |                      |                      |                      |                      |                      |                      |                             |    |    |    |                                     |  |  |  |
|      |                    | -0.025x10 <sup>-6</sup> | 0.025x10 <sup>-6</sup> | 0.05x10 <sup>-6</sup> | 0.05x10 <sup>-6</sup> | 0.1x10 <sup>-6</sup> | 0.1x10 <sup>-6</sup> | 0.1x10 <sup>-6</sup> | 0.1x10 <sup>-6</sup> | 0.1x10 <sup>-6</sup> | 0.1x10 <sup>-6</sup> | 0.1x10 <sup>-6</sup> | 0.1x10 <sup>-6</sup> | 0.1x10 <sup>-6</sup> | 0.1x10 <sup>-6</sup> | 0.1x10 <sup>-6</sup> | 0.1x10 <sup>-6</sup>        | 1X | 2X | 4  |                                     |  |  |  |
| 1    | 1                  | 1                       | 1                      | 1                     | 1                     | 1                    | 1                    | 1                    | 1                    | 1                    | 1                    | 1                    | 1                    | 1                    | 1                    | 1                    | 1                           | 1  | 8  |    |                                     |  |  |  |
| 2    | 3                  | 3                       | 3                      | 3                     | 3                     | 3                    | 3                    | 3                    | 3                    | 3                    | 3                    | 3                    | 3                    | 3                    | 3                    | 3                    | 3                           | 2  | 3  | 9  |                                     |  |  |  |
| 3    | 2                  | 2                       | 2                      | 2                     | 2                     | 2                    | 2                    | 2                    | 2                    | 2                    | 2                    | 2                    | 2                    | 2                    | 2                    | 2                    | 2                           | 3  | 2  | 6  |                                     |  |  |  |
| 4    | 4                  | 4                       | 4                      | 4                     | 4                     | 4                    | 4                    | 4                    | 4                    | 4                    | 4                    | 4                    | 4                    | 4                    | 4                    | 4                    | 4                           | 4  | 4  | 3  |                                     |  |  |  |
| 5    | 5                  | 5                       | 5                      | 5                     | 5                     | 5                    | 5                    | 5                    | 5                    | 5                    | 5                    | 5                    | 5                    | 5                    | 5                    | 5                    | 5                           | 1  | 5  | 8  |                                     |  |  |  |
| 6    | 6                  | 6                       | 6                      | 6                     | 6                     | 6                    | 6                    | 6                    | 6                    | 6                    | 6                    | 6                    | 6                    | 6                    | 6                    | 6                    | 6                           | 4  | 6  | 12 |                                     |  |  |  |
| 7    | 10                 | 10                      | 10                     | 10                    | 10                    | 10                   | 10                   | 10                   | 10                   | 10                   | 10                   | 10                   | 10                   | 10                   | 10                   | 10                   | 10                          | 8  | 9  | 1  |                                     |  |  |  |
| 8    | 8                  | 8                       | 8                      | 8                     | 8                     | 8                    | 8                    | 8                    | 8                    | 8                    | 8                    | 8                    | 8                    | 8                    | 8                    | 8                    | 8                           | 12 | 10 | 5  |                                     |  |  |  |
| 9    | 11                 | 11                      | 11                     | 11                    | 11                    | 11                   | 11                   | 11                   | 11                   | 11                   | 11                   | 11                   | 11                   | 11                   | 11                   | 11                   | 11                          | 10 | 11 | 10 |                                     |  |  |  |
| 10   | 9                  | 9                       | 9                      | 9                     | 9                     | 9                    | 9                    | 9                    | 9                    | 9                    | 9                    | 9                    | 9                    | 9                    | 9                    | 9                    | 9                           | 10 | 5  | 11 |                                     |  |  |  |
| 11   | 12                 | 12                      | 12                     | 12                    | 12                    | 12                   | 12                   | 12                   | 12                   | 12                   | 12                   | 12                   | 12                   | 12                   | 12                   | 12                   | 12                          | 12 | 12 | 2  |                                     |  |  |  |

\* Base Year Fuel Price Multipliers

\*\* Budgets are : \$12 x 10<sup>6</sup>; \$13.5 x 10<sup>6</sup>; \$16 x 10<sup>6</sup>.

TABLE 5-6 - RANKING OF ALTERNATIVES FOR DIFFERENT DECISION CRITERIA

(NO CORRELATION)

| Rank | RANKING CRITERION |                             |    |    |    |         |    |    |    |                            |    |    |    |   |    |    |    |                          |    |    |    |                        |    |    |    |
|------|-------------------|-----------------------------|----|----|----|---------|----|----|----|----------------------------|----|----|----|---|----|----|----|--------------------------|----|----|----|------------------------|----|----|----|
|      | Capital Cost      | EXPECTED UTILITY            |    |    |    |         |    |    |    |                            |    |    |    | P[ICC < $-12 \times 10^{-6}$<br>$-13.5 \times 10^{-6}$<br>$-16 \times 10^{-6}$<br>= min.] |    |    |    |                          |    |    |    |                        |    |    |    |
|      |                   | $s = -0.025 \times 10^{-6}$ |    |    |    | $s = 0$ |    |    |    | $s = 0.025 \times 10^{-6}$ |    |    |    | $s = 0.05 \times 10^{-6}$   |    |    |    | $s = 0.1 \times 10^{-6}$ |    |    |    | P[LOC < loc]<br>= 0.15 |    |    |    |
|      |                   | 1x                          | 2x | 4x | 1x | 2x      | 4x | 1x | 2x | 4x                         | 1x | 2x | 4x | 1x  | 2x | 4x | 1x | 2x                       | 4x | 1x | 2x | 4x                     | 1x | 2x | 4x |
| 1    | 1                 | 1                           | 1  | 1  | 1  | 1       | 1  | 1  | 1  | 1                          | 1  | 1  | 1  | 1   | 1  | 1  | 1  | 1                        | 1  | 1  | 1  | 1                      | 1  | 1  |    |
| 2    | 3                 | 3                           | 3  | 3  | 3  | 3       | 3  | 3  | 3  | 3                          | 3  | 3  | 3  | 3   | 3  | 3  | 3  | 3                        | 3  | 3  | 3  | 3                      | 3  | 3  |    |
| 3    | 2                 | 2                           | 4  | 2  | 2  | 4       | 2  | 2  | 6  | 2                          | 2  | 6  | 2  | 2   | 2  | 2  | 2  | 8                        | 1  | 11 | 9  | 3                      | 6  | 9  |    |
| 4    | 4                 | 4                           | 2  | 4  | 4  | 6       | 4  | 4  | 4  | 4                          | 4  | 8  | 4  | 4   | 4  | 4  | 9  | 6                        | 8  | 8  | 4  | 2                      | 8  |    |    |
| 5    | 5                 | 6                           | 6  | 5  | 6  | 2       | 5  | 6  | 11 | 5                          | 6  | 1  | 5  | 6   | 6  | 11 | 6  | 6                        | 11 | 6  | 6  | 5                      | 12 | 6  |    |
| 6    | 6                 | 5                           | 10 | 6  | 5  | 8       | 6  | 5  | 8  | 6                          | 5  | 12 | 6  | 5   | 10 | 5  | 9  | 10                       | 6  | 8  | 6  | 8                      | 10 |    |    |
| 7    | 10                | 10                          | 8  | 10 | 10 | 11      | 10 | 10 | 5  | 10                         | 10 | 9  | 10 | 11  | 3  | 4  | 5  | 3                        | 11 | 5  | 3  |                        |    |    |    |
| 8    | 8                 | 8                           | 11 | 8  | 8  | 10      | 8  | 8  | 12 | 8                          | 11 | 10 | 11 | 10  | 4  | 12 | 1  | 4                        | 10 | 9  | 5  |                        |    |    |    |
| 9    | 11                | 11                          | 9  | 11 | 11 | 9       | 11 | 11 | 9  | 11                         | 8  | 4  | 8  | 8   | 5  | 10 | 10 | 5                        | 8  | 4  | 4  |                        |    |    |    |
| 10   | 9                 | 9                           | 12 | 9  | 9  | 12      | 9  | 9  | 10 | 12                         | 12 | 2  | 12 | 12  | 1  | 9  | 2  | 2                        | 12 | 10 | 1  |                        |    |    |    |
| 11   | 12                | 12                          | 5  | 12 | 12 | 5       | 12 | 12 | 2  | 9                          | 9  | 5  | 9  | 9   | 2  | 8  | 4  | 1                        | 9  | 11 | 2  |                        |    |    |    |

TABLE 5-7 - RANKING OF ALTERNATIVES FOR DIFFERENT DECISION CRITERIA

(WITH CORRELATION)

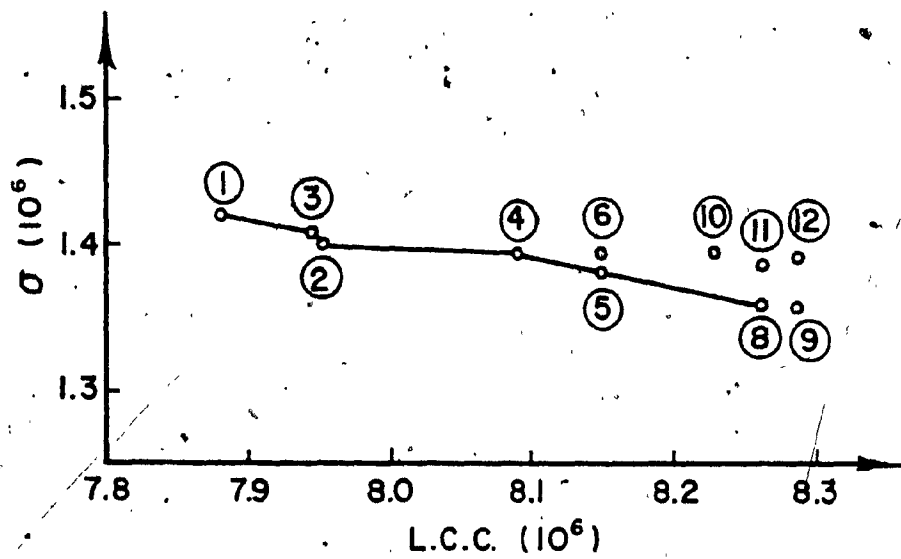


FIG. 5-6-EFFICIENT FRONTIER LINE FOR 1x

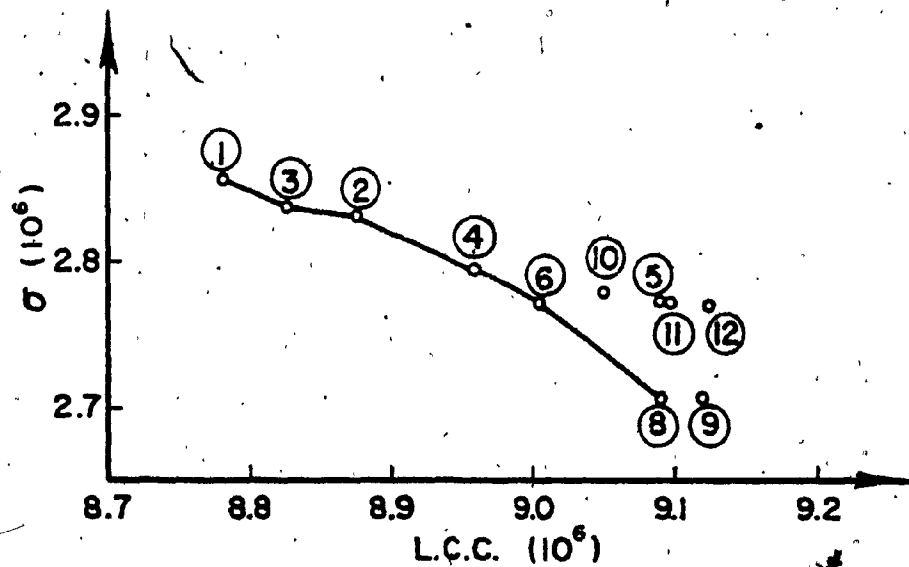


FIG. 5-7 - EFFICIENT FRONTIER LINE FOR 2x

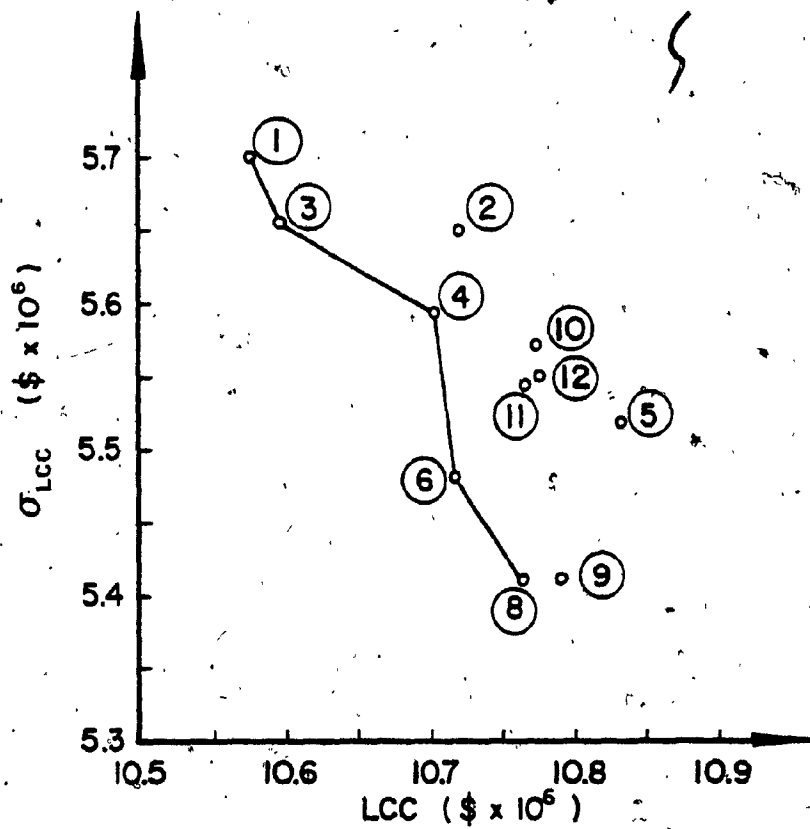


FIG. 5-8 - EFFICIENT FRONTIER FOR LINE 4x

### 5.3 SENSITIVITY ANALYSIS

In order to conduct the sensitivity analysis for life-cycle cost, some key parameters in the life-cycle cost equation should be chosen. In the previous chapters, time components of future costs were identified as a main source of risk. Therefore, it is worthwhile to observe how sensitive life-cycle cost and risk are with respect to time. Figure (5.9) shows how life-cycle cost and risk increase exponentially with time, how the gap increases between different multipliers of base year costs and why study of future time models was emphasized (correlation between different cost items are ignored).

Another parameter which is selected for sensitivity analysis is the tax rate. Its effect on life-cycle cost and risk were discussed in Chapters 1 and 2. Figure (5.10) demonstrates the fact that, as the tax rate increases, life-cycle cost and risk decreased substantially. For public developments, where there is no tax consideration, both life-cycle cost and risk have the highest values. This value decreases as the tax rate increases. For a private owner, who pays 50% tax, the risk decreases almost by 30% and life-cycle cost decreases by almost four million dollars.

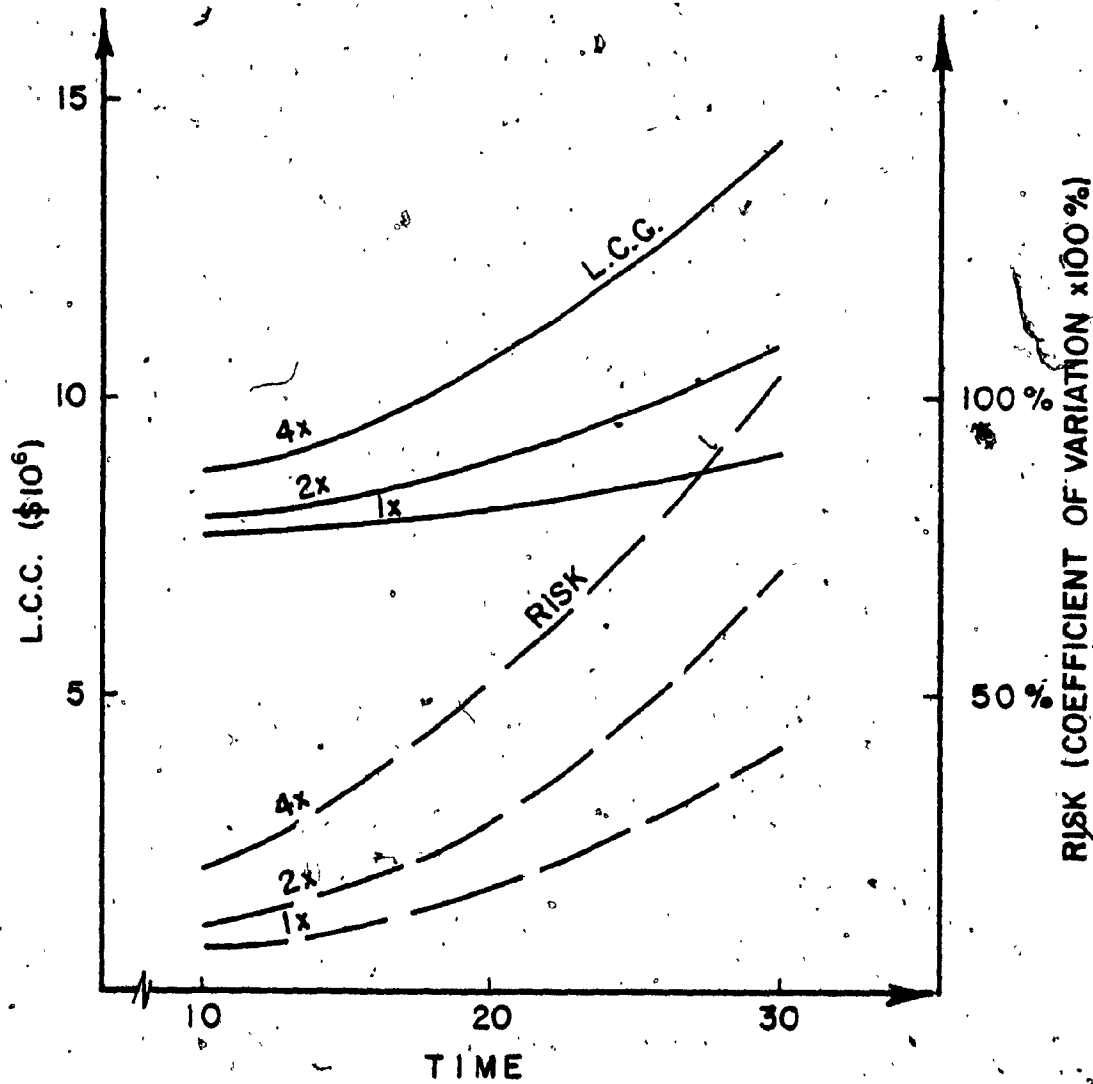


FIG. 5-9

TIME EFFECT OF LIFE CYCLE COST AND RISK



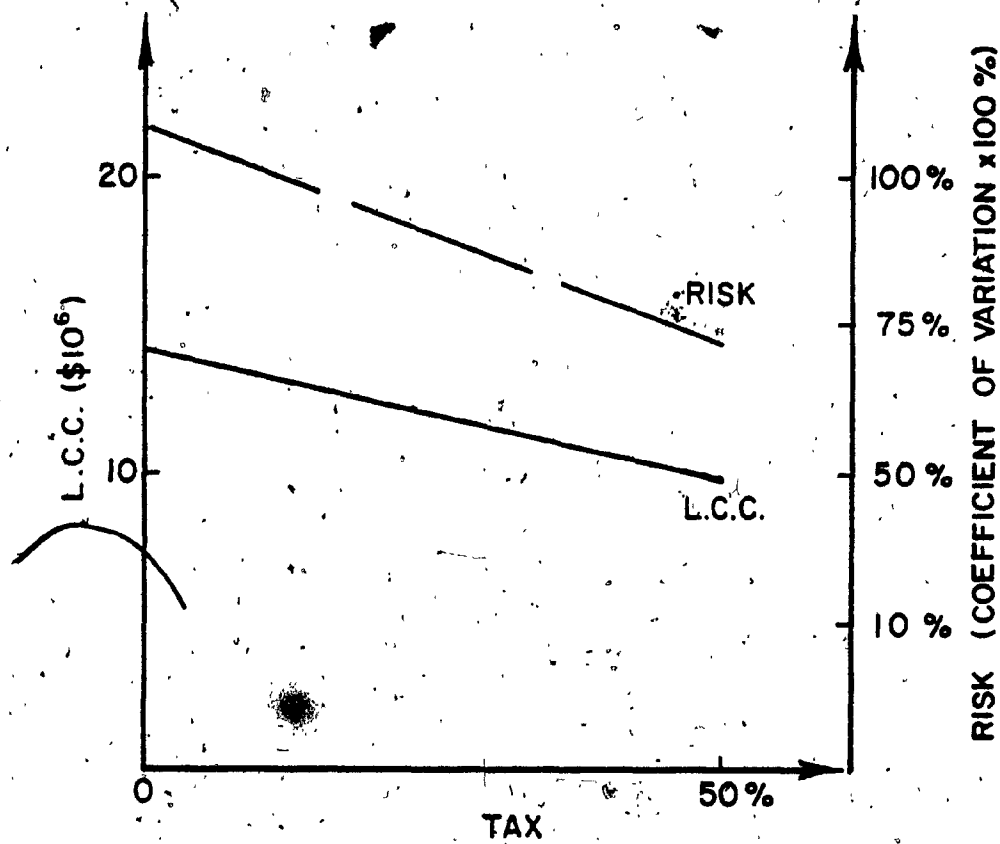


FIG. 5-10  
TAX RATE EFFECT OF LIFE CYCLE COST AND RISK

## CHAPTER 6

6.1 The objectives set forth in this thesis were :

- i) To develop a detailed statement of an objective function which measures life-cycle cost;
- ii) To demonstrate how risk can be measured and quantified for the life-cycle cost;
- iii) To show how risk can enter into the decision-making process;
- iv) To develop an interactive computer package to be used for assessing the relative merits of various decisions; and
- v) To examine an actual case study to demonstrate the significance of risk and the sensitivity of alternative rankings to different ranking criteria.

These goals have been met. In particular, a comprehensive relationship for life-cycle cost which treats all phases in the project life-cycle and the breadth of investor types has been developed. To facilitate a life-cycle cost analysis, a work breakdown structure similar to the Uniformat structure is suggested. The significance of time modeling in life-cycle cost is emphasized. It is asserted that the first step in time modeling is the determination of future inflation scenarios, in which the inflation rate can vary with time. Relationships are given for the present worth of these time models. Sources of uncertainty in the life-cycle cost equation are investigated. A first and second moment approach to measuring and quantifying this uncertainty is proposed, and the methodology is described in detail.

Maximization of expected utility is suggested as an objective function, as it incorporates both expected life-cycle cost and a measure of its variation. A computer aid based on the life-cycle-cost model developed was prepared and applied to a case study to demonstrate sources of risk, their relative magnitude and the sensitivity of rankings of alternatives to different decision criteria, including capital cost, life cycle cost and expected utility of life cycle cost. It was demonstrated that the choice of a design alternative can vary depending on the decision criteria adopted.

#### 6.2 RECOMMENDATIONS

Topics which should be treated in future work include :

1. Development of a methodology for decision making for problems characterized by multiple attributes and uncertainty;
2. Incorporation of preliminary analysis and design routines in the life-cycle cost computer package developed;
3. Development of a data base to permit multiple computer sessions on the same problem; and
4. Addition of optimization techniques, using both single-attributed and multi-attributed decision criteria, and for deterministic and probabilistic formulations.

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APPENDIX A

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|                | CASE3              | 134         |
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UNIVERSITY OF MINNESOTA FORTRAN COMPILER (VERSION 5.2 - 78/05/06) ON THE C172 UNDER N O S 1.1.0 ON 81/04/01 AT 15.09

HNF,I=LIFES,R=O,B=O.

PROGRAM LIFE (INPUT,OUTPUT,TAPE10,TAPE20)

LIFE CYCLE COST ANALYSIS

DEFINITION OF VARIABLES

R=AFTER TAX RATE OF RETURN  
TO=STARTING TIME OF CONSTRUCTION  
TE=STUDY PERIOD

LEVEL 1 (BUILDING SYSTEM LEVEL)  
\*\*\*\*\*

ELC=MEAN VALUE OF LIFE CYCLE COST  
ULC=VARIANCE OF LIFE CYCLE COST  
SDLC=STANDARD DEVIATION OF LIFE CYCLE COST  
CC=MEAN VALUE OF CAPITAL COST  
VC=VARIANCE OF CAPITAL COST

D,G,F=COEFFICIENTS OF UTILITY FUNCTION

LEVEL 2 (SUBSYSTEM LEVEL)  
\*\*\*\*\*

ELS=MEAN VALUE OF LIFE CYCLE COST AT SUBSYSTEM LEVEL  
ULS=VARIANCE OF LIFE CYCLE COST AT SUBSYSTEM LEVEL  
SDS=STANDARD DEVIATION OF LIFE CYCLE COST AT SUBSYSTEM LEVEL  
CC1=MEAN VALUE OF CAPITAL COST OF A SUBSYSTEM  
VC1=VARIANCE OF CAPITAL COST OF A SUBSYSTEM

LEVEL 3 (ELEMENT LEVEL)  
\*\*\*\*\*

E=MEAN VALUE OF LIFE CYCLE COST OF AN ELEMENT ALTERNATIVE  
U=VARIANCE OF LIFE CYCLE COST OF AN ELEMENT ALTERNATIVE  
SD=STANDARD DEVIATION OF LIFE CYCLE COST OF AN ELEMENT ALTERNATIVE  
EU=EXPECTED UTILITY OF LIFE CYCLE COST OF AN ELEMENT ALTERNATIVE  
CC2=MEAN VALUE OF CAPITAL COST OF AN ELEMENT ALTERNATIVE  
VC2=VARIANCE OF CAPITAL COST OF AN ELEMENT ALTERNATIVE

FUTURE COSTS

\*\*\*\*\*

CB=BASE YEAR COST OF A FUTURE COST COMPONENT  
PDCO=COEFFICIENT OF VARIATION OF BASE YEAR COST \*CO  
EB(N)=TIME FACTOR OF A FUTURE COST COMPONENT (E.G. OPERATING)  
VB=VARIANCE OF TIME FACTOR B  
SDB(N)=STANDARD DEVIATION OF TIME FACTOR B  
A1,A2,A3=COEFFICIENTS OF INFLATION MODEL  
P(1)=PROBABILITY OF OCCURRENCE OF MODEL

CN=BASE YEAR COST OF REPAIR AND ALTERATION  
 PDCN=COEFFICIENT OF VARIATION OF BASE YEAR COST 'CN'  
 EBS=TIME FACTOR FOR CAPITAL COST ALLOWANCE

COMMON R,TE,TO  
 COMMON /NAMES/ SUBSYS(20,3),ELEMNT(20,10,3),BNAME(4,2)  
 COMMON /HASH/ ITAB(2001),BUF20(21)  
 DIMENSION ER(4),SUB(4),C(4),DC(4)

INTEGER SUBSYS,ELEMNT,BNAME  
 DATA ((SUBSYS(1,N),N=1,2),I=1,20) /'FOUNDATION',S  
 'SUBSTRUCTU',RE  
 'SUPERSTRUC',TURE  
 'EXTERIOR C',LOSURE  
 'ROOFING',  
 'INTERIOR C',ONSTR.  
 'CONVEYING',SYSTEMS  
 'MECHANICAL',SYSTEMS  
 'ELECTRICAL',SYSTEMS  
 'GEN. COND.',PROFIT  
 'EQUIPMENT',  
 'SITENWORK',  
 16\*

DATA ((ELEMNT(1,J,N),N=1,2),J=1,10) /'STAND. FOU',NDATIONS  
 'SPEC. FOUN',DAT. COND.  
 16\*

DATA ((ELEMNT(2,J,N),N=1,2),J=1,10) /'SLAB ON GR',ADE  
 'BASEMENT E',ACAVATION  
 'BASEMENT W',ALL  
 14\*

DATA ((ELEMNT(3,J,N),N=1,2),J=1,10) /'FLOOR CONS',TRUCTION  
 'ROOF CONS',TRUCTION  
 'STAIR CONS',TRUCTION  
 14\*

DATA ((ELEMNT(4,J,N),N=1,2),J=1,10) /'EXTERIOR W',ALLS  
 'EXT. DOORS',WINDOWS  
 16\*

DATA ((ELEMNT(5,J,N),N=1,2),J=1,10) /'PARTITIONS',  
 'INTERIOR F',FINISHES  
 'SPECIALTIE',S  
 14\*

DATA ((ELEMNT(6,J,N),N=1,2),J=1,10) /'PLUMBING',  
 'HVAC',  
 'FIRE PROTE',CTION  
 'SPEC. MECH',SYSTEMS  
 12\*

DATA ((ELEMNT(7,J,N),N=1,2),J=1,10) /'SERVICE &',DISTRIB.  
 'LIGHTING &',POWER  
 'SPEC. ELEC',SYSTEMS  
 14\*

DATA ((ELEMNT(8,J,N),N=1,2),J=1,10) /'FIX. & MOV',ABLE EQUIP.  
 'FURNISHING',S  
 'SPECIAL CO',NSTRUCTION  
 14\*

DATA ((ELEMNT(9,J,N),N=1,2),J=1,10) /'SITE PREPA',RATION  
 'SITE IMPRO',UEMENTS  
 'SITE UTILI',TIES  
 'OFF-SITE W',ORK  
 12\*

DATA ((ELEMNT(10,J,N),N=1,2),J=1,10) /'SITE PREPA',RATION  
 'SITE IMPRO',UEMENTS  
 'SITE UTILI',TIES  
 'OFF-SITE W',ORK  
 12\*

DATA ((ELEMNT(11,J,N),N=1,2),J=1,10) /'SITE PREPA',RATION  
 'SITE IMPRO',UEMENTS  
 'SITE UTILI',TIES  
 'OFF-SITE W',ORK  
 12\*

DATA ((ELEMNT(12,J,N),N=1,2),J=1,10) /'SITE PREPA',RATION  
 'SITE IMPRO',UEMENTS  
 'SITE UTILI',TIES  
 'OFF-SITE W',ORK  
 12\*



```

20. 006261B DATA ((NAME(I,J),J=1,2),I=1,4) /OPERATING **COST
      "MAINTENANC",E COST
      "REPAIR & R",ENEM, COST
      "PERIODIC R",EPAIR COST/

21. 006261B CALL INIT & CACL OPENS (20,ITAB,2001,0)
23. 006305B PRINT 15 & READ *, R,T
25. 006315B 15 FORMAT (//,"INPUT THE RATE OF RETURN AND TAX RATE",
      //,"(INFLATION ADJUSTED AFTER TAX RATE OF RETURN)**"
26. 006315B PRINT 25 & READ *, TOPT & TE=TOPT
29. 006326B 25 FORMAT (//,"INPUT INITIAL TIME AND PERIOD OF STUDY")
30. 006326B PRINT 35 & READ *, D,B,F
32. 006340B 35 FORMAT (//,"INPUT THE COEFFICIENTS OF THE UTILITY FUNCTION")
33. 006340B ELC=VLC=SDLC=CC=VC=0.0

34. 006342B I=1 & INOW=21
36. 006344B 10 ELS=VLS=SDS=CC1=VC1=0.0
37. 006347B IF (SUBSYS(I),I,NE,10H) GO TO 20
38. 006352B PRINT 45 & READ 55, (SUBSYS(I,N),N=1,2)
40. 006371B 45 FORMAT (//,"INPUT THE NAME OF THIS SUBSYSTEM (MAX. 20 CHARS)")
41. 006371B 55 FORMAT (2A10)
42. 006371B 20 PRINT 65, (SUBSYS(I,N),N=1,2)
43. 006404B 65 FORMAT (//,"LEVEL 1, SUBSYSTEM 1, 2A10,/,57(//,*,*)
      //,"DO YOU WANT TO ANALYZE THIS SUBSYSTEM ? (Y/N)*"
44. 006404B READ 75, IANS & IF (IANS.EQ.1HN) GO TO 170
47. 006410B 75 FORMAT (A1)

48. 006412B J=1 & INOW=1
49. 006414B 30 E=U=SD=EU=CC2=VC2=0.0
50. 006420B IF (ELEMNT(I,J,1),NE,10H) GO TO 40
51. 006425B PRINT 85 & READ 55, (ELEMNT(I,J,N),N=1,2)
53. 006446B 85 FORMAT (//,"INPUT THE NAME OF THIS ELEMENT (MAX. 20 CHARS)")
54. 006446B 40 PRINT 95, (ELEMNT(I,J,N),N=1,2)
55. 006463B 95 FORMAT (//,"LEVEL 2, ELEMENT 1, 2A10,/,2K,55(//,*,*)
      //,"DO YOU WANT TO ANALYZE THIS ELEMENT ? (Y/N)*"
56. 006463B READ 75, IANS & IF (IANS.EQ.1HN) GO TO 160
58. 006470B 50 PRINT 105 & READ *, NALTER
60. 006500B 105 FORMAT (//,"4X,"INPUT THE NUMBER OF ALTERNATIVES (LE 10)*"
61. 006500B IF (NALTER.LE.0.OR.NALTER.GT.10) GO TO 50

62. 006502B IFLAG=1 & K=1 & JNOW=J
65. 006505B 40 PRINT 115, K
66. 006512B 115 FORMAT (//,"4X,"LEVEL 2, ALTERNATIVE NO *,12,/,4X,53(//,*,*)
      //,"6X,"INPUT THE ESTIMATED CAPITAL COST AND",
      //,"6X,"ITS PERCENTAGE OF EXPECTED ERROR")
67. 006512B READ *, CO,PDCO & VCO=(PDCO*CO)*2 & KEY=1+10000+J*100+K
70. 006524B PD=0.0 & CI=CO & M=PT & SUBSYS(I,3)=1 & ELEMNT(I,J,3)=NALTER
75. 006534B DO 70 N=1,M
76. 006536B PD=PD+CI*.05*EXP((-R)*(10+M)) & CI=CI-PD
78. 006551B 70 CONTINUE
79. 006555B EPS=PD/(CO*.05) & IF (CO.EQ.0.0) EPS=0.0 & MD=0
82. 006562B EL=CO-PDAT & VL=VCO-VCDX(I*EPS*.05)*2
84. 006571B PRINT 116 & READ 75, IANS
86. 006601B 116 FORMAT (//,"6X,"DO YOU HAVE ANY FUTURE COST CONFINIT ? (Y/N)*"
87. 006601B IF (IANS.EQ.1HN) MD=1

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```

88. DO 130 N=1,4
89.   EB(N)=UB=C(N)=PDC(N)=0.0
90.   IF (NO.EQ.1) GO TO 120
91.   PRINT 125, (BNAME(N,M),M=1,2)
92.   FORMAT (/,'X',:2A10,' ',:2A10,' ')
93.   //,'X','DO YOU WANT TO ANALYZE THIS COMPONENT ? (Y/N)')
94.   READ 75, IANS
95.   IF (IANS.EQ.1) GO TO 120
96.   PRINT 135 $ READ $, C(N),PDC(N)
97.   FORMAT ('X',:ITS PERCENTAGE OF EXPECTED ERROR')
98.   //,'X',:ITS PERCENTAGE OF EXPECTED ERROR')
99.   PRINT 145 $ READ $, ICASE
100.  FORMAT (/,'X',:INPUT INFLATION CATEGORY (1-3)')
101.  IF (ICASE.LT.1.OR.ICASE.GT.3) GO TO 80
102.  IF (ICASE.NE.2.OR.N.LE.2) GO TO 90
103.  PRINT 155 $ GO TO 80
104.  FORMAT (/,'X',:CATEGORY NO. 2 CANNOT BE USED FOR',
105.  : THIS COMPONENT')
106.  C 90 IF (ICASE.NE.1) GO TO 100
107.  CALL CASE1 (N,EB(N),UB)
108.  PRINT 165, EB(N),UB $ GO TO 120
109.  FORMAT (/,'X',:THE VALUES OF B FUNCTION 1',2F15.0)
110.  C 100 IF (ICASE.NE.2) GO TO 110
111.  CALL CASE2 (EB(N),UB)
112.  PRINT 165, EB(N),UB $ GO TO 120
113.  C 110 CALL CASE3 (N,EB(N),UB)
114.  PRINT 165, EB(N),UB
115.  C 120 SDB(N)=SQRT(UB)
116.  V1=C(N)*EB(N)
117.  V2=C(N)*EB(N)*V2=(PDC(N)*C(N))**2
118.  V2=C(N)*EB(N)*V2+V2*EB(N)**2+V2*UB
119.  EL=EL+V1*(1-T) $ UL=UL+V2*(1-T)**2
120.  C 130 CONTINUE
121.  CALL SAVE (KEY,CO,PCO,EB5,C,PDC,EB,SDB)
122.  C
123.  C
124.  C
125.  SDB=SQRT(UL)
126.  PRINT 175, EL,SDB
127.  FORMAT (/,'X',:THE EXPECTED VALUE OF L.C.C 1',F19.0,
128.  : 'X',:THE STANDARD DEVIATION OF L.C.C 1',F15.0)
129.  EUL=D188ELT+FX(UL,EL**2)
130.  IF (EUL.LT.EU) GO TO 140
131.  IF (IFLAG.EQ.0) GO TO 150
132.  EU=EUL $ E=EL $ V=UL $ SDB=SDB
133.  IFLAG=0 $ CC2=CO $ VC2=VCO $ KNOU=K
134.  150 K=K+1 $ IF (K.LE.NALTER) GO TO 60
135.  C
136.  C
137.  C
138.  ELB=EL$E $ ULB=UL$V
139.  CCI=CCI+CC2 $ VCI=VCI+VC2 $ SDB=SQRT(VCI)
140.  WRITE (10,*) INOW,JNOW,CC2,SP2,E,50,KNOU,EU
141.  IF (INOW.GT.0) INOW=-INOW
142.  C
143.  J=J+1 $ PRINT 185
144.  185 FORMAT (2X,55(' '),: ANYMORE ELEMENT ? (Y/N)')
145.  READ 75, IANS
146.  IF (IANS.NE.1) GO TO 30
147.  IF (J.GT.10) PRINT 195
148.  195 FORMAT (/,'X',:A SUBSYSTEM CANNOT HAVE MORE THAN 10 ELEMENTS')
149.  C
150.  C
151.  C
152.  C
153.  C
154.  C
155.  C

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155. 007071B C
156. 007074B C
157. 007104B C
158. 007121B C
159. 007122B C
160. 007123B C
161. 007124B C
162. 007125B C
163. 007126B C
164. 007127B C
165. 007128B C
166. 007129B C
167. 007130B C
168. 007131B C
169. 007132B C
170. 007133B C
171. 007134B C
172. 007135B C
173. 007136B C
174. 007137B C
175. 007138B C
176. 007139B C
177. 007140B C
178. 007141B C
179. 007142B C
180. 007143B C

```

SD1=SDRT(VLC) \* CC=CC+CC1 \* VC=VC+VC1  
SDS=SDRT(VLS) \* ELC=ELC+ELS \* VLC=VLC+VLS  
INOW=0 \* WRITE (10,\*) INOW,INOW,CC1,SD1,ELS,SDS,INOW,INOW  
170 I=I+1 \* PRINT 205  
205 FORMAT (57(' '),/, 'ANYMORE SUBSYSTEM ? (Y/N)')  
READ 75, IANS  
IF (IANS.NE.1HN.AND.1.LE.20) GO TO 10  
IF (1.07.20) PRINT 215  
215 FORMAT (/, '\*\*\* THE PROGRAM CAN SUPPORT ONLY 20 SUBSYSTEMS\*')  
IF (INOW.EQ.21) STOP  
SDLC=SDRT(VLC) \* SDC=SDRT(VLC) \* EULC=DIG\*ELC+IF\*(VLC-ELC\*\*2)  
INOW=21 \* WRITE (10,\*) (INOW,I=1,8)  
CALL OUTABS (PT,T,R,SDC,CC,SNLC,ELC,EULC)  
CALL RERUN (T,PT,D,G,F) \* CALL CLOSMS (20)  
STOP  
END

```

1. 0000008 SUBROUTINE OUTABS (PT,T,R,SDC,CC,SDLC,ELC,EULC)
2. 0000008 COMMON /NAMES/ SUBSYS(20,3),ELEMNT(20,10,3),BNAME(4,2)
3. 0000008 COMMON /HASH/ ITAB(2001),BUF20(21)
4. 0000008 DIMENSION EB(4),SDB(4),BUF(8)
5. 0000008 INTEGER SUBSYS,ELEMNT,BNAME,BUF

6. 0000008 REWIND 10
7. 0000228 PRINT 15, $ READ 25, IANS
9. 0000318 READ (10,35) (BUF(I),I=1,8) $ PRINT 45, (BUF(I),I=1,8)
11. 0000478 READ (10,35) (BUF(I),I=1,8) $ PRINT 55, (BUF(I),I=1,8)
13. 0000658 READ (10,35) (BUF(I),I=1,8) $ PRINT 65, (BUF(I),I=1,8)
15. 0001038 READ (10,35) (BUF(I),I=1,8) $ PRINT 75, (BUF(I),I=1,8)
17. 0001218 CALL TIME(BUF(1)) $ CALL DATE(BUF(2)) $ PRINT 85, BUF(1),BUF(2)
20. 0001328 READ (10,35) (BUF(I),I=1,8) $ PRINT 95, (BUF(I),I=1,8)
22. 0001508 PRINT 105, PT,T,R $ PRINT 115

24. 0001618 10 READ (10,*) I,J,CO,V1,C,V2,K,EL
25. 0001748 V1=V1/CD $ V2=V2/C
27. 0001778 IF (I.EQ.21) GO TO 20.
28. 0002018 IF (I.GT.0) PRINT 125, (SUBSYS(I,N),N=1,2), (ELEMNT(I,J,N),N=1,2),
29. 0002378 IF (I.LT.0) PRINT 135, (ELEMNT(-I,J,N),N=1,2), CO,V1,C,V2,K,EL
30. 0002658 IF (I.EQ.0) PRINT 145, CO,V1,C,V2
31. 0002758 GO TO 10

32. 0002758 20 V1=SDC/CC $ V2=SDLC/ELC
34. 0003018 PRINT 155, CC,V1,ELC,V2,EULC

35. 0003128 PRINT 165 $ READ 25, IANS
37. 0003218 IF (IANS.EQ.1NN) RETURN
38. 0003258 PRINT 175, (N,N=1,5)
39. 0003358 DO 100 I=1,20
40. 0003368 IF (SUBSYS(I,3).EQ.0) GO TO 100
41. 0003408 IFLAG=1
42. 0003408 DO 90 J=1,10
43. 0003428 IF (ELEMNT(I,J,3).EQ.0) GO TO 90
44. 0003468 DO 80 K=1,ELEMNT(I,J,3)
45. 0003548 KEY=I*10000+J*1000+K $ IQ=KEY/2000 $ IR=MOD(KEY,2000)
46. 0003658 LOC=IR $ IF (LOC.EQ.0) LOC=1
47. 0003718 IF (ITAB(LOC).EQ.0) GO TO 40
48. 0003738 LOC=MOD(LOC+IQ,2000) $ GO TO 30
49. 0003738 LOC=MOD(LOC+IQ,2000) $ GO TO 30
50. 0003738 LOC=MOD(LOC+IQ,2000) $ GO TO 30
51. 0003738 LOC=MOD(LOC+IQ,2000) $ GO TO 30
52. 0004008 CALL READMS (20,BUF20,21,LOC)
53. 0004038 EB5=BUF20(4) $ SDB5=BUF20(5) $ M=8
54. 0004068 DO 50 N=1,4
55. 0004108 EB(N)=BUF20(N) $ SDB(N)=BUF20(N+1) $ M=M+4
56. 0004148 CONTINUE
57. 0004158 IF (IFLAG.EQ.0) GO TO 60
58. 0004158 IF (IFLAG.EQ.0) GO TO 60
59. 0004158 PRINT 185, (SUBSYS(N,N),N=1,2), (ELEMNT(I,J,N),N=1,2),
60. 0004158 K,(EB(N),SDB(N),N=1,4),EB5,SDB5
61. 0004158 IF (K.GT.1) GO TO 70
62. 0004158 IF (K.GT.1) GO TO 70
63. 0004158 PRINT 195, (ELEMNT(I,J,N),N=1,2),K,
64. 0004158 (EB(N),SDB(N),N=1,4),EB5,SDB5
65. 0004208 GO TO 80
66. 0004218 PRINT 205, K,(EB(N),SDB(N),N=1,4),EB5,SDB5,
67. 0004638 CONTINUE
68. 0005158 GO TO 80
69. 0005158 PRINT 205, K,(EB(N),SDB(N),N=1,4),EB5,SDB5,
70. 0005348 CONTINUE
71. 0005368 CONTINUE
72. 0005418 CONTINUE
73. 0005448 PRINT 215

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74. 0005508 185 FORMAT (//, "MANUALLY GO TO A NEW PAGE AND INPUT A BLANK")
75. 0005508 25 FORMAT (A1)
76. 0005508 35 FORMAT (BA10)
77. 0005508 45 FORMAT (//, //, T20, "PROJECT NAME", T45, BA10)
78. 0005508 55 FORMAT (T20, "PROJECT DESCRIPTION", T45, BA10)
79. 0005508 65 FORMAT (T45, BA10)
80. 0005508 75 FORMAT (T20, "PROJECT LOCATION", T45, BA10)
81. 0005508 85 FORMAT (T20, "DATE OF ANALYSIS", T45, A10, " ON", A10)
82. 0005508 95 FORMAT (T20, "ARCH/ENG/DESIGNER", T45, BA10)
83. 0005508 105 FORMAT (//, T20, "PERIOD OF STUDY", T45, F7.0, 2X, "YEARS",
//, T20, "TAX RATE", T45, F6.3, //, T20, "NARR", T45, F6.3)
84. 0005508 115 FORMAT (//, T20, "LIFE CYCLE COST ANALYSIS",
//, T20, "F", T10, "LEVEL I", T26, "F", T35, "LEVEL II",
T51, "F", T56, "CAPITAL COST", T73, "F", T78, "LIFE CYCLE COST",
T98, "F", T104, "F", T120, "F", //, 2, "F", T24, "F", //, 14, "F",
//, 6, "F", //, 17, "F", //, 6, "F", //,
//, ALT, "UTILITY VALUE", //, //, "SUBSYSTEM", T26, "F",
T35, "ELEMENT", T51,
//, "CAPITAL COST * RISK * LIFE CYCLE COST * RISK", T104,
//, T120, "F", //, 120, "F", //,
T104, "F", T120, "F", //,
2, "F", 2X, 2A10, 2X, "F", 2X, F10.0, 2X, "F", 5.3, "F", 4X,
F10.0, 3X, "F", F5.3, "F", 2X, 2A10, 2X, "F", 2X, F10.0, 2X, "F", 5.3, "F",
4X, F10.0, 3X, "F", F5.3, "F", 2X, 12, "F", F14.0, "F",
145 FORMAT (T26, "F", T51, "F", T66, "F", T73, "F", T91, "F", T98, "F",
T104, "F", T120, "F", //, 2, "F", 24, "F", //, 14, "F", //,
6, "F", //, 17, "F", //, 6, "F", //, 5, "F", //, 15, "F",
//, "F", T10, "SUB-TOTAL", T26, "F", T51, "F", 2X, F10.0, 2X,
//, F5.3, "F", 2X, F10.0, 3X, "F", F5.3, "F", T104, "F", T120,
//, 2, "F", 24, "F", //, 14, "F", //, 6, "F", //,
17, "F", //, 6, "F", //, 5, "F", //, 15, "F", //,
T26, "F", T51, "F", T66, "F", T73, "F", T91, "F", T98, "F",
T104, "F", T120, "F", //, "F", T10, "GRAND TOTAL",
//, F5.3, "F", T104, "F", F14.0, "F", //, 120, "F", //,
165 FORMAT (//, "DO YOU WANT TO HAVE A TABLE OF ALL",
//, "THE B VALUES", Y/N, //,
175 FORMAT (//, //, 132, "F", //, "F", T10, "LEVEL I", T26, "F", T35,
//, "LEVEL II", T51, "F", //, 5, "F", 5, "F", 11, 6X, "F", //,
2, "F", 24, "F", //, "F", ALT, "F", 5, "F", 7, "F", //,
//, T9, "SUBSYSTEM", T26, "F", T35, "ELEMENT", T51, "F",
//, 5, "F", 88, "F", //, 132, "F", //,
185 FORMAT (T26, "F", T51, "F", //, 5, 6X, "F", 7X, "F", //,
2, "F", 2X, 2A10, 2X, "F", //, 13, "F", 5, "F", 6.1, "F", F6.2, "F",
//, T26, "F", 2X, 2A10, 2X, "F", //, 13, "F", 5, "F", 6.1, "F", F6.2, "F",
//, T26, "F", T51, "F", //, 13, "F", 5, "F", 6.1, "F", F6.2, "F",
//, T26, "F", T51, "F", //, 13, "F", 5, "F", 6.1, "F", F6.2, "F",
//, 132, "F", //, 132, "F", //,
95. 0005508 RETURN
96. 0005508 END

```

SUBROUTINE INIT  
COMMON /NAMES/, SUBSYS(20,3), ELEHNT(20,10,3), BNAME(4,2),  
INTEGER BUF(8), SUBSYS, ELEHNT, BNAME

REWIND 10  
PRINT 15  
READ 25, (BUF(I), I=1,8) \* WRITE (10,25) (BUF(I), I=1,8)  
PRINT 35  
READ 25, (BUF(I), I=1,8) \* WRITE (10,25) (BUF(I), I=1,8)  
READ 25, (BUF(I), I=1,8) \* WRITE (10,25) (BUF(I), I=1,8)  
PRINT 45  
READ 25, (BUF(I), I=1,8) \* WRITE (10,25) (BUF(I), I=1,8)  
PRINT 55  
READ 25, (BUF(I), I=1,8) \* WRITE (10,25) (BUF(I), I=1,8)

DO 20 J=1,10  
DO 10 I=1,20  
ELEHNT(I,J,1)=ELEHNT(I,J,2)=10H

10 CONTINUE  
20 CONTINUE

DO 40 I=1,20  
SUBSYS(I,3)=0  
DO 30 J=1,10  
ELEHNT(I,J,3)=0

30 CONTINUE  
40 CONTINUE

15 FORMAT (///, 'INPUT THE NAME OF THE PROJECT (MAX. 80 CHARS)')  
25 FORMAT (B410)

35 FORMAT (/, 'INPUT 2 LINES FOR THE DESCRIPTIONS OF THE PROJECT',  
/, ' (MAX. 80 CHARS PER LINE)')

45 FORMAT (/, 'INPUT THE LOCATION OF THE PROJECT')  
55 FORMAT (/, 'INPUT THE NAME OF THE DESIGNER(S)')

RETURN  
END

1. 000000B  
2. 000000B  
3. 000000B

000000B  
000012B  
000013B  
000013B  
000033B  
000036B  
000054B  
000072B  
000075B  
000113B  
000113B  
000114B

000134B  
000135B  
000137B  
000137B  
000143B  
000144B  
000150B  
000150B  
000153B  
000153B  
000161B

000163B  
000163B  
000163B  
000163B  
000163B  
000163B

000163B  
000165B

SUBROUTINE SAVE (K,CD,PCO,EB5,C,PDC,EB,SDB)  
COMMON /HASH/ ITAB(2001),BUF20(21)  
DIMENSION EB(4),SDB(4),C(4),PDC(4)

1. 0000008  
2. 0000008  
3. 0000008

BUF20(1)=K \$ BUF20(2)=CD \$ BUF20(3)=PCO  
BUF20(4)=EB5 \$ BUF20(5)=0.0 \$ J=6  
DO 10 I=1,4

4. 0000008  
7. 000003B  
10. 000007B

BUF20(J)=C(I) \$ BUF20(J+1)=PDC(I)  
BUF20(J+2)=EB(I) \$ BUF20(J+3)=SDB(I) \$ J=J+4

11. 000011B  
13. 000013B  
14. 000020B

10 CONTINUE

IG=K/2000 \$ IR=MOD(K,2000)  
LOC=IR \$ IF (LOC.EQ.0) LOC=1  
20 IF (ITAB(LOC).EQ.0) GO TO 30  
LOC=MOD(LOC+IG,2000) \$ GO TO 20

17. 000021B  
19. 000024B  
21. 000032B  
22. 000033B

30 ITAB(LOC)=K \$ CALL WRITB (20,BUF20,21,LOC)

24. 000040B

RETURN  
END

26. 000045B  
27. 000047B

```

SUBROUTINE RERUN (T,PT,D,G,F)
COMMON R,TE,TD
COMMON /NAMES/ SUBSYS(20,3),ELEMNT(20,10,3),BNAME(4,2)
COMMON /HASH/ ITH(2001),RUF20(21)
INTEGER SUBSYS,ELEMNT,BNAME,NAME(2)

1. 00000008
2. 00000008
3. 00000008
4. 00000008
5. 00000008

C C C
6. 00000008
8. 0000118
9. 0000118
10. 0000118
11. 0000158
13. 0000248
14. 0000248
15. 0000258
17. 0000368
18. 0000368
20. 0000458
21. 0000458
22. 0000458
23. 0000608
27. 0000708
28. 0000708
29. 0000718

C C C
31. 0001038
33. 0001158
34. 0001158
35. 0001158
36. 0001158
37. 0001178
38. 0001238
39. 0001258
40. 0001268
43. 0001328
43. 0001328
44. 0001348
47. 0001408
47. 0001408

C C C
48. 0001418
50. 0001558
51. 0001558
52. 0001558
53. 0001578
54. 0001668
55. 0001708
56. 0001718
59. 0001758
59. 0001758
60. 0002028
60. 0002058
63. 0002058

SUBROUTINE RERUN (T,PT,D,G,F)
COMMON R,TE,TD
COMMON /NAMES/ SUBSYS(20,3),ELEMNT(20,10,3),BNAME(4,2)
COMMON /HASH/ ITH(2001),RUF20(21)
INTEGER SUBSYS,ELEMNT,BNAME,NAME(2)

10 PRINT 15 $ READ 25, IANS
15 FORMAT (////, "DO YOU WANT TO CHANGE SOME DATA ")
FOR ANOTHER RUN ? (Y/N)*)
25 FORMAT (A1)
IF (IANS.EQ.1HN) RETURN
PRINT 35 $ READ 25, IANS
35 FORMAT (////, "DO YOU WANT TO CHANGE THE RATE OF RETURN ")
AND THE TAX RATE ? (Y/N)*)
IF (IANS.EQ.1HN) GO TO 20
PRINT 45 $ READ $, R,T
45 FORMAT (//, "INPUT THEIR NEW VALUES")
20 PRINT 55 $ READ 25, IANS
55 FORMAT (A//, "DO YOU WANT TO CHANGE THE INITIAL TIME ")
AND THE PERIOD OF STUDY ? (Y/N)*)
IF (IANS.EQ.1HN) GO TO 30
PRINT 45 $ READ $, TO,PT $ TE=TO+PT
30 PRINT 65 $ READ 25, IANS
65 FORMAT (////, "DO YOU WANT TO CHANGE THE COEFFICIENTS ")
OF THE UTILITY FUNCTION ? (Y/N)*)
IF (IANS.EQ.1HN) GO TO 40
PRINT 45 $ READ $, D,G,F

40 PRINT 75 $ READ 85, (NAME(N),N=1,2)
75 FORMAT (//, "WHAT SUBSYSTEM DO YOU WANT TO CHANGE")
85 FORMAT (2A10)
IFOUND=0
DO 50 I=1,20
IF (SUBSYS(I,1).EQ.NAME(1)) IFOUND=1
50 CONTINUE
IF (IFOUND.NE.0) GO TO 60
PRINT 95 $ GO TO 40
95 FORMAT (//, "THIS SUBSYSTEM DOES NOT EXIST, PLEASE RE-ENTER")
60 IF (SUBSYS(IFOUND,3).NE.0) GO TO 70
PRINT 105 $ GO TO 40
105 FORMAT (//, "THIS SUBSYSTEM WAS NOT INCLUDED IN YOUR PLAN, "
PLEASE RE-ENTER")
70, I=IFOUND

C C C
80 PRINT 115 $ READ 85, (NAME(N),N=1,2)
115 FORMAT (//, "WHICH ELEMENT OF THE SUBSYSTEM DO YOU WANT, "
"TO CHANGE")
IFOUND=0
DO 90 J=1,10
IF (ELEMNT(I,J,1).EQ.NAME(1)) IFOUND=J
90 CONTINUE
IF (IFOUND.NE.0) GO TO 100
PRINT 125 $ GO TO 80
125 FORMAT (//, "THERE IS NO SUCH AN ELEMENT, PLEASE RE-ENTER")
100 IF (ELEMNT(I,IFOUND,3).NE.0) GO TO 110
PRINT 135 $ GO TO 80
135 FORMAT (//, "THIS ELEMENT WAS NOT INCLUDED IN YOUR PLAN, "
PLEASE RE-ENTER")

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63. 000205B 110 J=IFOUND
64. 000206B 120 PRINT 145, ELEMNT(I,J,3) $ READ $, K
66. 000223B 145 FORMAT (/,"X","OF","I3," ALTERNATIVES, WHICH ONE DO YOU WANT ",
    "TO CHANGE")
67. 000223B IF (K,LT,0-OR,K,GT,ELEMNT(I,J,3)) GO TO 120
68. 000231B KEY=I*10000+J*100+K $ ID=KEY/2000 $ IR=MOD(KEY,2000)
71. 000243B LOC=IR $ IF (LOC.EQ,0) LOC=1
73. 000246B 130 IF (ITAB(LOC).EQ,KEY) GO TO 140.
74. 000250B LOC=MOD(LOC+10,2000) $ GO TO 130
76. 000255B 140 CALL READHS (20,BUF20,21,LOC) $ CALL PRINTREC (BUF20,LOC)
78. 000262B PRINT 155 $ READ 25, IANS
80. 000271B 155 FORMAT (/,"X","DO YOU WANT TO CHANGE THE ESTIMATED COST ",
    "AND ITS % OF ERROR ? (Y/N).")
81. 000271B IF (IANS.EQ,1HN) GO TO 160
82. 000272B PRINT 45 $ READ $, BUF20(2),BUF20(3)
84. 000303B PD=0.0 $ C1=BUF20(2) $ M=PT
87. 000306B DO 150 N=1,M
88. 000310B PD=PD+C1*.05*EXP((-R)*(TO+N)) $ C1=C1-PD
90. 000323B 150 CONTINUE
91. 000327B BUF20(4)=PD/(BUF20(2)*.05) $ IF (BUF20(2).EQ,0.0) BUF20(4)=0.0
93. 000334B 160 PRINT 165 $ READ 25, IANS
95. 000343B 165 FORMAT (/,"X","DO YOU WANT TO CHANGE ANY COMPONENT ? (Y/N).")
96. 000343B IF (IANS.EQ,1HN) GO TO 230
97. 000344B L=6
98. 000345B DO 220 N=1,L
99. 000347B VB=0.0
100. 000347B PRINT 175, (BNAME(N,H),H=1,2) $ READ 25, IANS
102. 000347B FORMAT (/,"X","==",2A10,"==",
    "//,"X","DO YOU WANT TO CHANGE THIS COMPONENT ? (Y/N).")
103. 000347B IF (IANS.EQ,1HN) GO TO 210
104. 000370B PRINT 185 $ READ 25, IANS
106. 000400B 185 FORMAT (/,"X","DO YOU WANT TO CHANGE THE BASE YEAR COST ",
    "AND ITS % OF ERROR ? (Y/N).")
107. 000400B IF (IANS.EQ,1HN) GO TO 170
108. 000401B PRINT 45 $ READ $, BUF20(L),BUF20(L+1)
110. 000414B PRINT 171 $ READ 25, IANS
112. 000423B FORMAT (/,"X","DO YOU WANT TO CHANGE INFLATION ? (Y/N).")
113. 000423B IF (IANS.EQ,1HN) GO TO 210
114. 000424B PRINT 195 $ READ $, ICASE
116. 000434B 170 FORMAT (/,"X","INPUT INFLATION CATEGORY (1-3).")
117. 000434B IF (ICASE.LT,1-OR,ICASE.GT,3) GO TO 170
118. 000437B IF (ICASE.NE,2-OR,N.LE,2) GO TO 180
119. 000443B PRINT 205 $ GO TO 170
122. 000447B 205 FORMAT (/,"*** CATEGORY NO. 2 CANNOT BE USED ",
    "FOR THIS COMPONENT.")
122. 000447B 180 IF (ICASE.NE,1) GO TO 190
123. 000451B CALL CASE1 (N,BUF20(L+2),VB) $ GO TO 210
125. 000455B 190 IF (ICASE.NE,2) GO TO 200
126. 000457B CALL CASE2 (BUF20(L+2),VB) $ GO TO 210
128. 000483B 200 CALL CASE3 (N,BUF20(L+2),VR)
129. 000467B BUF20(L+3)=SORT(VB)
130. 000471B L=L+4
131. 000473B 210 CONTINUE
132. 000476B 230 CALL PRINTREC (BUF20,LOC) $ CALL WRITHS (20,BUF20,21,LOC)
134. 000503B PRINT 215 $ READ 25, IANS
136. 000512B 215 FORMAT (/,"X","ANYMORE ALTERNATIVE ? (Y/N).")

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```

137. 000512B C IF (IANS.NE.1HN) GO TO 120
138. 000513B PRINT 225 $ READ 25, IANS
140. 000523B 225 FORMAT (/,' ANYMORE ELEMENT ? (Y/N)')
141. 000523B IF (IANS.NE.1HN) GO TO 80
142. 000524B PRINT 235 $ READ 25, IANS
144. 000534B 235 FORMAT (/,' ANYMORE SUBSYSTEM ? (Y/N)')
145. 000534B IF (IANS.NE.1HN) GO TO 40

146. 000535B REMIND 10
147. 000540B DO 240 I=1,5
148. 000541B READ (10,25) IANS
149. 000546B 240 CONTINUE

150. 000550B ELC=VLC=SDLC=CC=VC=0.0
151. 000553B DO 320 I=1,20
152. 000555B IF (SUBSYS(I,J).EQ.0) GO TO 320
153. 000557B ELS=VLS=SDS=CCI=VCI=0.0 $ INDM=I
155. 000562B DO 310 J=1,10
156. 000565B IF (ELEMNT(I,J,3).EQ.0) GO TO 310
157. 000571B E=U=SD=EU=CC2=VC2=0.0 $ IFLAG=1
159. 000575B DO 300 K=1,ELEMT(I,J,3)
160. 000604B KEY=I*10000+J*1000+K $ IQ=KEY/2000 $ IR=MOD(KEY,2000)
163. 000615B LOC=IR $ IF (LOC.EQ.0) LOC=1
165. 000621B IF (ITAB(LOC).EQ.KEY) GO TO 240
166. 000623B LOC=MOD(LOC+IQ,2000) $ GO TO 250
168. 000630B CALL READHS (20,BUF20,21,LOC)
169. 000633B VCU=(BUF20(3)*BUF20(2))**2
170. 000634B PD=0.0 $ CI=BUF20(2) $ M=PT
173. 000637B DO 270 N=1,M
174. 000641B PD=PD+CI*.05*EXP((-R)*(TO+N)) $ CI=CI-PD
176. 000654B CONTINUE
177. 000660B EL=BUF20(2)-PD*IT $ VL=VCO-VCO*(I*BUF20(4)*.05)**2
179. 000665B L=6
180. 000666B DO 280 N=1,4
181. 000670B ..V1=BUF20(L)*BUF20(L+2) $ V2=(BUF20(L+1)*BUF20(L))**2
183. 000673B V2=V2*(BUF20(L+2)**2+BUF20(L+3)**2)+
(BUF20(L)*BUF20(L+3))**2
EL=EL+V1*(1-T) $ VL=VL+V2*(1-T)**2 $ L=L+4
CONTINUE
SDL=SDRT(VL) $ EUL=DI*EL+IF*(VL+EL**2)
IF (EUL.LT.EU) GO TO 290
IF (IFLAG.EQ.0) GO TO 300
EU=EUL $ E=EL $ U=U $ SD=SRL
IFLAG=0 $ CC2=BUF20(2) $ VC2=VCO $ KNOW=K
CONTINUE
ELS=ELS+E $ VLS=VLS+V
CCI=CCI+CC2 $ VCI=VCI+VC2 $ SD2=SDRT(VC2)
WRITE (10,*) INDM,J,CC2,SD2,E,SD,KNOW,EU
IF (INDM.NE.0) INDM=-INDM

280 CONTINUE
290 CONTINUE
300 CONTINUE
310 CONTINUE
SDI=SDRT(VCI) $ CC=CCI+CCI $ VC=VC+VCI
SDS=SDRT(VLS) $ ELC=ELC+ELS $ VLC=VLC+VLS
INDM=0 $ WRITE (10,*) INDM,INDM,CCI,SDI,ELS,SDS,INDM,INDM
CONTINUE
SNLC=SDRT(VLC) $ SDC=SDRT(VC)
EULC=D+GVEL+FF*(VLC+ELC**2)
INDM=21 $ WRITE (10,*) (INDM,I=1,8)
CALL OUTANS (PT,T,R,SHC,CC,SNLC,ELC,FULC)
GO TO 10
224. 001060B

```

```
225. 001060B      END
      000000B      SUBROUTINE PRINREC (BUF,LOC)
      000000B      DIMENSION BUF(21)
      000000B      KEY=BUF(1) & PRINT 15, LOC,KEY,(BUF(1),1-2,21)
      000013B      15 FORMAT (80(' '),/, ' RECORD AT LOCATION',15, ' WITH KEY',17,
      000013B      /,8X,2(F15.0,F7.4),/,4(8X,2(F15.0,F7.4),/),80(' '))
      000013B      RETURN
      000013B      END
```

```

1. 0000008 SUBROUTINE CASE1 (N,EB,VB)
2. 0000008 COMMON R,TE,TD
3. 0000008 COMMON /COEFF/ A(3)
4. 0000008 COMMON /CONTRL/ XM,XJ,ICONTROL
5. 0000008 EXTERNAL F

6. 0000008 PRINT *, 'ENTER CASE 1' * VB=0.0
8. 0000058 10 PRINT 15 * READ *, MO
10. 0000158 15 FURMAT (6X,'CHOOSE INFLATION MODEL (1-4)')
11. 0000158 IF (MO.LT.1.OR.MO.GT.4) GO TO 10
12. 0000208 PRINT 25
13. 0000248 25 FURMAT (6X,'INPUT THE COEFF. OF THE INFLATION MODEL*')

14. 0000248 IF (MO.NE.1) GO TO 40
15. 0000258 READ *, A(1)
16. 0000328 IF (A(1).EQ.0) GO TO 30
17. 0000338 IF (N.LT.3) GO TO 90
18. 0000358 IF (ICONTROL.EQ.1) GO TO 20
19. 0000378 PRINT 35 * READ *, XM,XJ
21. 0000508 35 FURMAT (6X,'INPUT THE FIRST YEAR OF REPAIR AND ITS PERIOD*')
22. 0000508 20 AA=A(1)-R * GO TO 120
24. 0000528 30 EB=TE-TD * RETURN

26. 0000578 40 IF (MO.NE.2) GO TO 60
27. 0000608 READ *, A(1),A(2)
28. 0000648 IF (N.LT.3) GO TO 90
29. 0000678 IF (ICONTROL.EQ.1) GO TO 50
30. 0000718 PRINT 35 * READ *, XM,XJ
32. 0001028 50 AA=A(1)-A(2)/2.XM-R * GO TO 120

34. 0001078 60 IF (MO.NE.3) GO TO 80
35. 0001108 READ *, A(1),A(2)
36. 0001148 IF (N.LT.3) GO TO 90
37. 0001178 IF (ICONTROL.EQ.1) GO TO 70
38. 0001218 PRINT 35 * READ *, XM,XJ
40. 0001328 70 AA=A(1)+A(2)/2.XM-R * GO TO 120

42. 0001378 80 READ *, A(1),A(2),A(3)
43. 0001458 IF (N.GT.2) GO TO 100
44. 0001468 90 CALL INTERG (F,MO,TD,TE,EB,1.OE-7) * RETURN
46. 0001548 100 IF (ICONTROL.EQ.1) GO TO 110
47. 0001558 PRINT 35 * READ *, XM,XJ
49. 0001668 110 AA=A(2)+(A(1)-A(2))/(-A(3))*EXP(-A(3)*XM)-R
50. 0002008 120 EB=EXP(AA*XM)*(1.-EXP((TE-XM)*AA))/(1.-EXP(AA*XJ))

51. 0002238 RETURN
52. 0002268 END

```

```

1. 000000B
2. 000000B C C C
   SUBROUTINE CASE2 (EB,VB)
   COMMON R,TE,TO

3. 000000B
4. 000005B
5. 000014B
6. 000014B
7. 000014B
8. 000014B
9. 000020B
10. 000024B
11. 000024B
12. 000024B C
   PRINT 3, 'ENTER CASE 2'
10 PRINT 15 $ READ 3, EA,CV $ VA=(CV*EA)**2
15 FORMAT (4X,'INPUT THE INFLATION RATE AND COEFF. OF VARIATION')
   IF (EA.NE.R) GO TO 20
   PRINT 25 $ GO TO 10
25 FORMAT (/, '*** RE-INPUT YOUR DATA SINCE MARR CANNOT BE EQUAL *',
   ., TO INFLATION RATE')

20 EB=1/(EA-R)*(EXP((EA-R)*TE)-EXP((EA-R)*TO))
   +VA/2*(1/(EA-R)*(EXP((EA-R)*TE)*TE**2-EXP((EA-R)*TO)*TO**2)
   -2/(EA-R)**2*(EXP((EA-R)*TE)*TE-EXP((EA-R)*TO)*TO)
   +2/(EA-R)**3*(EXP((EA-R)*TE)-EXP((EA-R)*TO)))
   VB=VA*(1/(EA-R)*(EXP((EA-R)*TE)*TE-EXP((EA-R)*TO)*TO)
   -1/(EA-R)**2*(EXP((EA-R)*TE)-EXP((EA-R)*TO)))**2

13. 000060B C C C
   RETURN
14. 000102B
15. 000105B
   END

```

```

1. 000000B
2. 000000B
3. 000000B

SUBROUTINE CASE3 (N,EB,UB)
COMMON /CONTRL/ XM,XJ,ICONTRL
DIMENSION EBN(20),P(20)

PRINT *, "ENTER CASE 3"
EB=UB-PR=0.0 & I=1 & ICONTRL=0
IF (N.LT.3) GO TO 10
PRINT 15 & READ *, XM,XJ & ICONTRL=1
15 FORMAT (6X,"INPUT THE FIRST YEAR OF REPAIR AND ITS PERIOD")

10 CALL CASE1 (N,EBN(I),U)
PRINT 25 & READ *, P(I)
25 FORMAT (6X,"INPUT THE PROBABILITY OF THE MODEL")
PR=PR+P(I) & IF (PR.GT.1.0) GO TO 20
EBN(I)=EBN(I)*P(I) & EB=EB+EBN(I)
IF (PR.EQ.1.0) GO TO 30
PRINT 35 & READ 45, IANS
35 FORMAT (6X,"DO YOU HAVE MORE MODELS ? (Y/N)")
45 FORMAT (A1)
IF (IANS.EQ.1) GO TO 30
I=I+1 & GO TO 10

20 PRINT 35
55 FORMAT (/,,"*** STATE OF NATURE DOES NOT PERMIT TO CHOOSE",
/,"6X,"THIS MODEL WITH THIS PROBABILITY.")
PR=PR-P(I) & GO TO 10

30 DO 40 J=1,I
UB=UB+(EBN(J)/P(J)-EB)**2*P(J)
40 CONTINUE

RETURN
END

36. 000153B
37. 000155B

```

```

1. 000000B
2. 000000B
3. 000000B
   C
4. 000000B
5. 000011B
6. 000023B
7. 000035B
   C
8. 000056B
9. 000061B

```

FUNCTION F(T,H)  
COMMON R,TE,TD  
COMMON /COEFF/ A(3)  
IF (H.EQ.1) F=EXP((A(1)-R)\*T)  
IF (H.EQ.2) F=EXP((A(1)-A(2))/2.\*T-R)\*T)  
IF (H.EQ.3) F=EXP((A(1)+A(2))/2.\*T-R)\*T)  
IF (H.EQ.4) F=EXP((A(2)+(A(1)-A(2))/(-A(3))\*EXP(-A(3)\*T)-R)\*T)  
RETURN  
END

SUBROUTINE INTERO (F,M,A,B,S,DEL)  
EXTERNAL F

```

1. 000000B
2. 000000B
   C
3. 000000B
   C
4. 000003B
   C
5. 000004B
6. 000007B
7. 000007B
8. 000020B
9. 000031B
10. 000031B
11. 000041B
12. 000041B
13. 000046B
14. 000051B
15. 000051B
16. 000052B
17. 000054B
   C
18. 000056B
19. 000056B
20. 000056B
21. 000062B
   C
22. 000064B
   C
23. 000064B
   C
24. 000064B
   C
25. 000064B
   C
26. 000105B
27. 000107B

```

S=0.0 \$ X=A \$ H=0.1  
10 ISTAT=1  
20 X1=X+H \$ X2=X1+H  
S1=(F(X,M)+F(X1,M))/2.\*H  
S2=(F(X1,M)+F(X2,M))/2.\*H  
S3=(F(X,M)+F(X2,M))\*H  
IF (ABS(S3-S1-S2).GT.DEL) GO TO 30  
H=H\*2.0 \$ IF (ISTAT.EQ.0) GO TO 40  
GO TO 20  
30 IF (ISTAT.NE.0) ISTAT=0  
H=H/2.0 \$ GO TO 20  
40 DB=S3  
IF ((X+H).GT.B) GO TO 50  
S=S+DB \$ X=X+H. \$ GO TO 10  
50 DS=(F(X,M)+F(B,M))\*X\*(B-X)/2.0 \$ S=S+DS  
RETURN  
END

INPUT THE NAME OF THE PROJECT (MAX. 80 CHARS)  
? PROGRAM LIFE

INPUT 2 LINES FOR THE DESCRIPTIONS OF THE PROJECT  
(MAX. 80 CHARS PER LINE)  
? LIFE CYCLE COST ANALYSIS

INPUT THE LOCATION OF THE PROJECT  
? CENTER FOR BUILDING STUDIES

INPUT THE NAME OF THE DESIGNER(S)  
? ALI-ARLANI

INPUT THE RATE OF RETURN AND TAX RATE  
(INFLATION ADJUSTED AFTER TAX RATE OF RETURN)  
? .15,0

INPUT INITIAL TIME AND PERIOD OF STUDY  
? 1.5,30

INPUT THE COEFFICIENTS OF THE UTILITY FUNCTION  
? 0.1,0

LEVEL 1 : SUBSYSTEM 1 FOUNDATIONS  
\*\*\*\*\*

DO YOU WANT TO ANALYZE THIS SUBSYSTEM ? (Y/N)  
? NO  
\*\*\*\*\*  
ANYMORE SUBSYSTEM ? (Y/N)  
? YES

LEVEL 1 : SUBSYSTEM 1 SUBSTRUCTURE  
\*\*\*\*\*

DO YOU WANT TO ANALYZE THIS SUBSYSTEM ? (Y/N)  
? NO  
\*\*\*\*\*  
ANYMORE SUBSYSTEM ? (Y/N)  
? YES

LEVEL 1 : SUBSYSTEM 1 SUPERSTRUCTURE  
\*\*\*\*\*

DO YOU WANT TO ANALYZE THIS SUBSYSTEM ? (Y/N)  
? NO  
\*\*\*\*\*  
ANYMORE SUBSYSTEM ? (Y/N)  
? YES

LEVEL 1 : SUBSYSTEM 1 EXTERIOR CLOSURE  
\*\*\*\*\*

DO YOU WANT TO ANALYZE THIS SUBSYSTEM ? (Y/N)  
? YES

LEVEL 2 : ELEMENT 1 EXTERIOR WALLS



DO YOU WANT TO ANALYZE THIS ELEMENT ? (Y/N)  
? YES

INPUT THE NUMBER OF ALTERNATIVES (LE 10)  
? 1

LEVEL 2 ,ALTERNATIVE NO 1

INPUT THE ESTIMATED CAPITAL COST AND  
ITS PERCENTAGE OF EXPECTED ERROR  
? 2984701.025

DO YOU HAVE ANY FUTURE COST COMPONENT ? (Y/N)  
? NO

THE EXPECTED VALUE OF L.C.C IS 2984701.  
THE STANDARD DEVIATION OF L.C.C IS 74618.

ANYMORE ELEMENT ? (Y/N)  
? NO  
ANYMORE SUBSYSTEM ? (Y/N)  
? YES

LEVEL 1 , SUBSYSTEM : ROOFING  
\*\*\*\*\*  
DO YOU WANT TO ANALYZE THIS SUBSYSTEM ? (Y/N)  
? NO  
ANYMORE SUBSYSTEM ? (Y/N)  
? YES

LEVEL 1 , SUBSYSTEM : INTERIOR CONSTR.  
\*\*\*\*\*  
DO YOU WANT TO ANALYZE THIS SUBSYSTEM ? (Y/N)  
? NO  
ANYMORE SUBSYSTEM ? (Y/N)  
? YES

LEVEL 1 , SUBSYSTEM : CONVEYING SYSTEMS  
\*\*\*\*\*  
DO YOU WANT TO ANALYZE THIS SUBSYSTEM ? (Y/N)  
? NO  
ANYMORE SUBSYSTEM ? (Y/N)  
? YES

LEVEL 1 , SUBSYSTEM : MECHANICAL SYSTEMS  
\*\*\*\*\*  
DO YOU WANT TO ANALYZE THIS SUBSYSTEM ? (Y/N)  
? YES

LEVEL 2, ELEMENT : PLUMBING

DO YOU WANT TO ANALYZE THIS ELEMENT ? (Y/N)

? NO

ANYMORE ELEMENT ? (Y/N)

? YES

LEVEL 2, ELEMENT : HVAC

DO YOU WANT TO ANALYZE THIS ELEMENT ? (Y/N)

? YES

INPUT THE NUMBER OF ALTERNATIVES (LE 10)

? 1

LEVEL 2, ALTERNATIVE NO 1

INPUT THE ESTIMATED CAPITAL COST AND ITS PERCENTAGE OF EXPECTED ERROR

? 2380808,025

DO YOU HAVE ANY FUTURE COST COMPONENT ? (Y/N)

? YES

--- OPERATING COST ---

DO YOU WANT TO ANALYZE THIS COMPONENT ? (Y/N)

? YES

INPUT THE ESTIMATED BASE YEAR COST AND ITS PERCENTAGE OF EXPECTED ERROR

? 21845,1

INPUT INFLATION CATEGORY (1-3)

? 3

ENTER CASE 3

ENTER CASE 1

CHOOSE INFLATION MODEL (1-4)

? 1

INPUT THE COEFF. OF THE INFLATION MODEL

? .25

INPUT THE PROBABILITY OF THE MODEL

? .025

DO YOU HAVE MORE MODELS ? (Y/N)

? YES

ENTER CASE 1

CHOOSE INFLATION MODEL (1-4)

? 3

INPUT THE COEFF. OF THE INFLATION MODEL

? .25,0025

INPUT THE PROBABILITY OF THE MODEL

? .025

DO YOU HAVE MORE MODELS ? (Y/N)

? YES

ENTER CASE 1

CHOOSE INFLATION MODEL (1-4)

? 4

INPUT THE COEFF. OF THE INFLATION MODEL

? .25,1,34

INPUT THE PROBABILITY OF THE MODEL

? .2

DO YOU HAVE MORE MODELS ? (Y/N)

```

? YES
ENTER CASE 1
CHOOSE INFLATION MODEL (1-4)
? 4 INPUT THE COEFF. OF THE INFLATION MODEL
? .25?1?1?17
INPUT THE PROBABILITY OF THE MODEL
? .4 DO YOU HAVE MORE MODELS ? (Y/N)
? YES
ENTER CASE 1
CHOOSE INFLATION MODEL (1-4)
? 4 INPUT THE COEFF. OF THE INFLATION MODEL
? .25?1?1?113
INPUT THE PROBABILITY OF THE MODEL
? .2 DO YOU HAVE MORE MODELS ? (Y/N)
? YES
ENTER CASE 1
CHOOSE INFLATION MODEL (1-4)
? 4 INPUT THE COEFF. OF THE INFLATION MODEL
? .25?1?1?085
INPUT THE PROBABILITY OF THE MODEL
? .15

THE VALUES OF B FUNCTION : 22. 6704.
=== MAINTENANCE COST ===
DO YOU WANT TO ANALYZE THIS COMPONENT ? (Y/N)
? NO

=== REPAIR & RENEW. COST ===
DO YOU WANT TO ANALYZE THIS COMPONENT ? (Y/N)
? NO

=== PERIODIC REPAIR COST ===
DO YOU WANT TO ANALYZE THIS COMPONENT ? (Y/N)
? NO

THE EXPECTED VALUE OF L.C.C : 2871541.
THE STANDARD DEVIATION OF L.C.C : 1800796.
ANYMORE ELEMENT ? (Y/N)
? YES

LEVEL 2 ELEMENT : FIRE PROTECTION
=====
DO YOU WANT TO ANALYZE THIS ELEMENT ? (Y/N)
? NO
ANYMORE ELEMENT ? (Y/N)
? YES

LEVEL 2 ELEMENT : SPEC. MECH. SYSTEMS
=====
DO YOU WANT TO ANALYZE THIS ELEMENT ? (Y/N)

```

? NO  
 =====  
 ANYMORE ELEMENT ? (Y/N)  
 ? YES  
 ?  
 INPUT THE NAME OF THIS ELEMENT (MAX. 20 CHARS)  
 ? CHILLER  
 ?  
 LEVEL 2 ELEMENT : CHILLER  
 =====  
 DO YOU WANT TO ANALYZE THIS ELEMENT ? (Y/N)  
 ? YES  
 ?  
 INPUT THE NUMBER OF ALTERNATIVES (LE 10)  
 ? 1  
 LEVEL 2 ALTERNATIVE NO 1  
 =====  
 INPUT THE ESTIMATED CAPITAL COST AND  
 ITS PERCENTAGE OF EXPECTED ERROR  
 ? 0.0  
 ?  
 DO YOU HAVE ANY FUTURE COST COMPONENT ? (Y/N)  
 ? YES  
 ?  
 \*\*\* OPERATING COST \*\*\*  
 DO YOU WANT TO ANALYZE THIS COMPONENT ? (Y/N)  
 ? YES  
 ?  
 INPUT THE ESTIMATED BASE YEAR COST AND  
 ITS PERCENTAGE OF EXPECTED ERROR  
 ? 7663.1  
 ?  
 INPUT INFLATION CATEGORY (1-3)  
 ? 3  
 ENTER CASE 3  
 ENTER CASE 1  
 CHOOSE INFLATION MODEL (1-4)  
 ? 1  
 INPUT THE COEFF. OF THE INFLATION MODEL  
 ? .2  
 INPUT THE PROBABILITY OF THE MODEL  
 ? .025  
 DO YOU HAVE MORE MODELS ? (Y/N)  
 ? YES  
 ENTER CASE 1  
 CHOOSE INFLATION MODEL (1-4)  
 ? 3  
 INPUT THE COEFF. OF THE INFLATION MODEL  
 ? .2.0025  
 INPUT THE PROBABILITY OF THE MODEL  
 ? .025  
 DO YOU HAVE MORE MODELS ? (Y/N)  
 ? YES  
 ENTER CASE 1  
 CHOOSE INFLATION MODEL (1-4)  
 ? 4  
 INPUT THE COEFF. OF THE INFLATION MODEL  
 ? .2.075.32  
 INPUT THE PROBABILITY OF THE MODEL  
 ? .2  
 DO YOU HAVE MORE MODELS ? (Y/N)  
 ? YES

```

ENTER CASE 1
CHOOSE INFLATION MODEL (1-3)
? 4
  INPUT THE COEFF. OF THE INFLATION MODEL
  ? 2.075.14
  INPUT THE PROBABILITY OF THE MODEL
  ? .4
  DO YOU HAVE MORE MODELS ? (Y/N)
  ? YES
ENTER CASE 1
CHOOSE INFLATION MODEL (1-4)
? 4
  INPUT THE COEFF. OF THE INFLATION MODEL
  ? 2.075.107
  INPUT THE PROBABILITY OF THE MODEL
  ? .2
  DO YOU HAVE MORE MODELS ? (Y/N)
  ? YES
ENTER CASE 1
CHOOSE INFLATION MODEL (1-4)
? 4
  INPUT THE COEFF. OF THE INFLATION MODEL
  ? 2.075.08
  INPUT THE PROBABILITY OF THE MODEL
  ? .15
  THE VALUES OF B FUNCTION :      9.      612.
  --- MAINTENANCE COST ---
  DO YOU WANT TO ANALYZE THIS COMPONENT ? (Y/N)
  ? NO
  --- REPAIR & RENEW. COST ---
  DO YOU WANT TO ANALYZE THIS COMPONENT ? (Y/N)
  ? NO
  --- PERIODIC REPAIR COST ---
  DO YOU WANT TO ANALYZE THIS COMPONENT ? (Y/N)
  ? NO
  THE EXPECTED VALUE OF L.C.C !      67450.
  THE STANDARD DEVIATION OF L.C.C !      190569.
  ANYMORE ELEMENT ? (Y/N)
  ? NO
  ANYMORE SUBSYSTEM ? (Y/N)
  ? YES
  LEVEL 1, SUBSYSTEM 1 ELECTRICAL SYSTEMS
  *****
  DO YOU WANT TO ANALYZE THIS SUBSYSTEM ? (Y/N)
  ? YES
  LEVEL 2, ELEMENT 1 SERVICE & DISTRI.
  *****
  DO YOU WANT TO ANALYZE THIS ELEMENT ? (Y/N)
  ? NO
  
```

=====

ANYMORE ELEMENT ? (Y/N)

7 YES

=====

LEVEL 2 ,ELEMENT : LIGHTING & POWER

=====

DO YOU WANT TO ANALYZE THIS ELEMENT ? (Y/N)

7 YES

INPUT THE NUMBER OF ALTERNATIVES (LE 10)

7 1

LEVEL 2 ,ALTERNATIVE NO 1

=====

INPUT THE ESTIMATED CAPITAL COST AND  
ITS PERCENTAGE OF EXPECTED ERROR

7 1626900,.025

DO YOU HAVE ANY FUTURE COST COMPONENT ? (Y/N)

7 YES

=== OPERATING COST ===

DO YOU WANT TO ANALYZE THIS COMPONENT ? (Y/N)

7 YES

INPUT THE ESTIMATED BASE YEAR COST AND  
ITS PERCENTAGE OF EXPECTED ERROR

7 147092,.1

INPUT INFLATION CATEGORY (1-3)

7 3

ENTER CASE 3.

ENTER CASE 1

CHOOSE INFLATION MODEL (1-4)

7 1

INPUT THE COEFF. OF THE INFLATION MODEL

7 .2

INPUT THE PROBABILITY OF THE MODEL

7 .025

DO YOU HAVE MORE MODELS ? (Y/N)

7 YES

ENTER CASE 1

CHOOSE INFLATION MODEL (1-4)

7 3

INPUT THE COEFF. OF THE INFLATION MODEL

7 .2,.0025

INPUT THE PROBABILITY OF THE MODEL

7 .025

DO YOU HAVE MORE MODELS ? (Y/N)

7 YES

ENTER CASE 1

CHOOSE INFLATION MODEL (1-4)

7 4

INPUT THE COEFF. OF THE INFLATION MODEL

7 .2,.075,.32

INPUT THE PROBABILITY OF THE MODEL

7 .2

DO YOU HAVE MORE MODELS ? (Y/N)

7 YES

ENTER CASE 1

CHOOSE INFLATION MODEL (1-4)

7 4

INPUT THE COEFF. OF THE INFLATION MODEL

```

7 2.075.16
INPUT THE PROBABILITY OF THE MODEL
7 4 DO YOU HAVE MORE MODELS ? (Y/N)
7 YES
ENTER CASE 1
7 4 CHOOSE INFLATION MODEL (1-4)
INPUT THE COEFF. OF THE INFLATION MODEL
7 2.075.107
INPUT THE PROBABILITY OF THE MODEL
7 2 DO YOU HAVE MORE MODELS ? (Y/N)
7 YES
ENTER CASE 1
7 4 CHOOSE INFLATION MODEL (1-4)
INPUT THE COEFF. OF THE INFLATION MODEL
7 2.075.08
INPUT THE PROBABILITY OF THE MODEL
7 15
THE VALUES OF B FUNCTION : 9. 612.
=== MAINTENANCE COST ===
DO YOU WANT TO ANALYZE THIS COMPONENT ? (Y/N)
7 NO
=== REPAIR & RENEW. COST ===
DO YOU WANT TO ANALYZE THIS COMPONENT ? (Y/N)
7 NO
=== PERIODIC REPAIR COST ===
DO YOU WANT TO ANALYZE THIS COMPONENT ? (Y/N)
7 NO
THE EXPECTED VALUE OF L.C.C : 2921611.
THE STANDARD DEVIATION OF L.C.C : 3658219.
=====
ANYMORE ELEMENT ? (Y/N)
7 NO
*****
ANYMORE SUBSYSTEM ? (Y/N)
7 NO
MANUALLY GO TO A NEW PAGE AND INPUT A BLANK
7

```

PROJECT NAME  
PROJECT DESCRIPTION  
PROGRAM LIFE  
LIFE CYCLE COST ANALYSIS  
CENTER FOR BUILDING STUDIES  
13.45.15. ON 80/07/05.  
ALI-ARLANI  
PERIOD OF STUDY 30. YEARS  
TAX RATE 0  
HARR .150

LIFE CYCLE COST ANALYSIS

| LEVEL I            | LEVEL II | ELEMENT          | CAPITAL COST | RISK | LIFE CYCLE COST | RISK  | ALT. UTILITY VALUE |
|--------------------|----------|------------------|--------------|------|-----------------|-------|--------------------|
| SUBSYSTEM          |          |                  |              |      |                 |       |                    |
| EXTERIOR CLOSURE   |          | EXTERIOR WALLS   | 2984700.     | .025 | 2984700.        | .025  | 2984700.           |
| SUB-TOTAL          |          |                  | 2984700.     | .025 | 2984700.        | .025  |                    |
| MECHANICAL SYSTEMS |          | HVAC             | 2380810.     | .025 | 2871540.        | .627  | 2871540.           |
|                    |          | CHILLER          | 0            | 1    | 67450.          | 2.825 | 67450.             |
| SUB-TOTAL          |          |                  | 2380810.     | .025 | 2938990.        | .616  |                    |
| ELECTRICAL SYSTEMS |          | LIGHTING & POWER | 1626900.     | .025 | 2921610.        | 1.252 | 2921610.           |
| SUB-TOTAL          |          |                  | 1626900.     | .025 | 2921610.        | 1.252 |                    |
| GRAND TOTAL        |          |                  | 6992409.     | .015 | 8845303.        | .462  | 8845303.           |

DO YOU WANT TO HAVE A TABLE OF ALL THE B VALUES ? (Y/N)  
7 YES PLEASE



| LEVEL I            | LEVEL II         | ALT | B1   | B2    | B3 | B4 | B5 |
|--------------------|------------------|-----|------|-------|----|----|----|
| SUBSYSTEM          | ELEMENT          | EB  | SB   | EB    | SB | EB | SB |
| EXTERIOR CLOSURE   | EXTERIOR WALLS   | 1   | 0    | 0     | 0  | 0  | 0  |
| MECHANICAL SYSTEMS | HVAC             | 1   | 22.4 | 81.88 | 0  | 0  | 0  |
|                    | CHILLER          | 1   | 8.8  | 24.73 | 0  | 0  | 0  |
| ELECTRICAL SYSTEMS | LIGHTING & POWER | 1   | 8.8  | 24.73 | 0  | 0  | 0  |

DO YOU WANT TO CHANGE SOME DATA FOR ANOTHER RUN ? (Y/N)  
 YES PLEASE

DO YOU WANT TO CHANGE THE RATE OF RETURN AND THE TAX RATE ? (Y/N)  
 NO

DO YOU WANT TO CHANGE THE INITIAL TIME AND THE PERIOD OF STUDY ? (Y/N)  
 NO

DO YOU WANT TO CHANGE THE COEFFICIENTS OF THE UTILITY FUNCTION ? (Y/N)  
 NO

WHAT SUBSYSTEM DO YOU WANT TO CHANGE  
 MECHANICAL SYSTEMS

WHICH ELEMENT OF THE SUBSYSTEM DO YOU WANT TO CHANGE  
 HVAC

OF 1 ALTERNATIVES; WHICH ONE DO YOU WANT TO CHANGE  
 1

RECORD AT LOCATION 201 WITH KEY 80201

|          |       |       |      |
|----------|-------|-------|------|
| 2380808. | .0250 | 2.    | 0    |
| 21845.   | .1000 | 22.81 | 8758 |
| 0        | 0     | 0     | 0    |
| 0        | 0     | 0     | 0    |
| 0        | 0     | 0     | 0    |

DO YOU WANT TO CHANGE THE ESTIMATED COST AND ITS % OF ERROR ? (Y/N)  
 NO

DO YOU WANT TO CHANGE ANY COMPONENT ? (Y/N)  
 YES

==OPERATING COST

DO YOU WANT TO CHANGE THIS COMPONENT ? (Y/N)

7 YES DO YOU WANT TO CHANGE THE BASE YEAR COST AND ITS % OF ERROR ? (Y/N)  
 7 YES  
 INPUT THEIR NEW VALUES  
 7 43730.1

7 NO DO YOU WANT TO CHANGE INFLATION

---MAINTENANCE COST ---

7 NO DO YOU WANT TO CHANGE THIS COMPONENT ? (Y/N)

---REPAIR & RENEW. COST---

7 NO DO YOU WANT TO CHANGE THIS COMPONENT ? (Y/N)

---PERIODIC REPAIR COST---

7 NO DO YOU WANT TO CHANGE THIS COMPONENT ? (Y/N)

RECORD AT LOCATION 201 WITH KEY 80201  
 2380808. .0250 2. 0  
 43730. .1000 22.81.8758  
 0 0 0 0  
 0 0 0 0  
 0 0 0 0

7 NO ANYMORE ALTERNATIVE ? (Y/N)

ANYMORE ELEMENT ? (Y/N)

7 YES

7 CHILLER WHICH ELEMENT OF THE SUBSYSTEM DO YOU WANT TO CHANGE

7 1 OF 1 ALTERNATIVES, WHICH ONE DO YOU WANT TO CHANGE

RECORD AT LOCATION 501 WITH KEY 80501

7643. .1000 0 0  
 0 0 9.24.7298  
 0 0 0 0  
 0 0 0 0  
 0 0 0 0

7 NO DO YOU WANT TO CHANGE THE ESTIMATED COST AND ITS % OF ERROR ? (Y/N)

7 YES DO YOU WANT TO CHANGE ANY COMPONENT ? (Y/N)

---OPERATING COST ---

7 YES DO YOU WANT TO CHANGE THIS COMPONENT ? (Y/N)

DO YOU WANT TO CHANGE THE BASE YEAR COST AND ITS % OF ERROR ? (Y/N)

Y YES

INPUT THEIR NEW VALUES  
T 15326, .1

DO YOU WANT TO CHANGE INFLATION

Y NO

---MAINTENANCE COST ---

DO YOU WANT TO CHANGE THIS COMPONENT ? (Y/N)

Y NO

---REPAIR & RENEW. COST---

DO YOU WANT TO CHANGE THIS COMPONENT ? (Y/N)

Y NO

---PERIODIC REPAIR COST---

DO YOU WANT TO CHANGE THIS COMPONENT ? (Y/N)

Y NO

RECORD AT LOCATION 501 WITH KEY 80501

|              |   |   |           |
|--------------|---|---|-----------|
| 15326, .1000 | 0 | 0 | 0         |
| 0            | 0 | 0 | 9,24,7298 |
| 0            | 0 | 0 | 0         |
| 0            | 0 | 0 | 0         |
| 0            | 0 | 0 | 0         |

ANYMORE ALTERNATIVE ? (Y/N)

Y NO

ANYMORE ELEMENT ? (Y/N)

Y NO

ANYMORE SUBSYSTEM ? (Y/N)

Y YES

WHAT SUBSYSTEM DO YOU WANT TO CHANGE  
T ELECTRICAL SYSTEMS

WHICH ELEMENT OF THE SUBSYSTEM DO YOU WANT TO CHANGE  
T LIGHTING SPONER

OF 1 ALTERNATIVES, WHICH ONE DO YOU WANT TO CHANGE

T 1

RECORD AT LOCATION 246 WITH KEY 90501

|                |           |   |
|----------------|-----------|---|
| 1626900, .0250 | 2, .      | 0 |
| 147092, .1000  | 9,24,7298 | 0 |
| 0              | 0         | 0 |
| 0              | 0         | 0 |
| 0              | 0         | 0 |

DO YOU WANT TO CHANGE THE ESTIMATED COST AND ITS % OF ERROR ? (Y/N)

Y NO

DO YOU WANT TO CHANGE ANY COMPONENT ? (Y/N)

Y YES